Determining an appropriate electricity supply mix for the Hessequa Municipality: A system dynamics approach

By

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Declaration

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Abstract

South Africa has a highly centralised, monopolistic and regulated electricity sector. Eskom is the country's national electricity utility and a state owned enterprise. Steep electricity tariff hikes have caused many consumers to invest in embedded generation technologies such as rooftop PV systems to reduce their dependence on grid-based electricity. Most of the defecting electricity consumers purchased electricity from a local government entity, who in turn purchased electricity directly from Eskom. Local governments often use profits from electricity sales to subsidise its various service delivery functions. A shrinking customer base on the local government level can thus threaten the financial viability of a municipality. Increases in electricity tariffs result in more customers investing in embedded generation causing the municipal customer base to shrink even more. This complex municipal system and its internal interactions are commonly referred to as the municipal dilemma.

The Hessequa local municipality, located in the Eden district of the Western Cape, is used as a case study to explore the possible impacts of the municipal dilemma on its electricity sector. In order to limit the potential negative impacts, local government wants to investigate the option of supplying a third of local electricity demand with renewable energy technology.

This study estimates the current and future demand for electricity in the Hessequa area based on population growth and economic growth. Various renewable energy technologies are evaluated along with renewable resource availability. A system dynamics model is used for simulating scenarios that test policies relating to renewable energy technology investment. The impacts of expanding the renewable energy generation capacity on the environment, socio-economic conditions and local government are investigated.

This study shows that both biomass (in the form of invasive alien plants) and solar resources are in sufficient supply to meet the municipality's goal of supplying its electricity demand through renewable electricity generation. Simulation results indicate that solar photo-voltaic (PV) energy is the most attractive renewable energy option in terms of capital cost and the cost of generated electricity. Biomass power is more expensive than solar PV in terms of capital cost and cost of generated electricity, but has better job creation potential and positive environmental impact due to invasive alien clearing. Simulation results further suggest that an appropriate renewable electricity supply mix would consist of a large portion solar PV and biomass power. The recommended electricity supply mix will require an estimated cumulative investment of R 679 million by 2040. The model also indicates

that significant CO_2 emission reductions up to 37% can be expected by the year 2040 relative to the case where no commercial scale renewable energy generation is established.

Opsomming

Suid-Afrika het 'n hoogs gesentraliseerde, monopolistiese en gereguleerde elektrisiteitsektor. Eskom is die land se nasionale kragvoorsiener en is ook 'n staatsbeheerde maatskappy. Skerp verhogings in elektrisiteitstariewehet daartoe gelei dat baie elektrisiteitsverbruikers investeer in kleinskaalse elektrisiteitsopwekkingskapasiteit soos PV sonkrag stelsels. Die doel met die investering is om verbruikers se afhanklikheid van die nasionale kragnetwerk te verminder. Die meerderheid van verbruikers wat oorskakel na hernubare kragvoorsiening het vroeër elektrisiteit gekoop by plaaslike regeringsinstellings, wie dit weer direk vanaf Eskom gekoop het. Die wins wat deur elektrisiteitsverkope gegenereer word, word dikwels deur plaaslike regerings gebruik om munisipale dienslewering te finansier of te subsidieer. Die krimpende kliëntebasis kan die plaaslike regering se finansiële volhoubaarheid bedreig. Daar word dikwels na hierdie komplekse stelsel en sy interaksies verwys as die munisipale dilemma.

Die Hessequa Plaaslike Munisipaliteit, geleë in die Eden distrik van die Wes-Kaap, word in hierdie studie gebruik as 'n gevallestudie om die moontlike impakte van die munisipale dilemma op die area se elektrisiteit sektor te ondersoek. In 'n poging om die negatiewe impakte van hierdie dilemma te beperk, wil plaaslike regering die opsie ondersoek om 'n derde van sy elektrisiteitsaanvraag te voorsien met behulp van hernubare energietegnologie.

Die studie skat die huidige en toekomstige elektrisiteitsaanvraag vir die Hessequa area vooruit op grond van bevolkingsgetalle en ekonomiese groei. Verkeie hernubare energietegnologieë word ge-evalueer tesame met plaaslike beskikbaarheid van hernubare energiebronne. 'n Stelsel dinamiese model is gebruik vir die simulasie van verskeie senario's wat beleide toets in verband met hernubare energie investering. Die impkate van hernubare energietegnologie op die omgewing, sosio-ekonomies omstandighede en die plaaslike regering word ondersoek.

Die studie bevind dat biomassa (in die vorm van indringerplante) asook sonkrag hulpbronne in die area voldoende behoort te wees vir elektrisiteitsopwekking ten einde die oogmerk te bereik om een derde van die totale munisipale elektriese energievraag uit hernubare energie te bevredig. Simulasie-resultate dui daarop dat sonkrag PV die aantreklikste opsie is in terme van kapitaalkoste per kW geïnstalleerde kapasiteit asook i.t.v. die eenheidskoste van elektrisiteitsopgewekking in Rand per kWh. Biomassa-gebaseerde elektrisiteit is duurder as sonkrag, maar het groter potensiaal vir werkskepping en gunstige omgewingsimpakte as gevolg van die uitroei van indringerplante.

Die simulasieresultate stel voor dat die mees gepaste hernubare elektrisiteitsvoorsieningsopsies sal bestaan uit 'n groot deel sonkrag en biomassa elektrisiteit. Die simulasies dui verder aan dat 'n geskatte R 679 miljoen se investering kumulatief benodig sal word teen 2040 om die voorgestelde tegnologieë te implementeer. Verder word daar aangedui dat CO_2 vrystelling teen 2040 met 37% kan verminder relatief tot die opsie wanneer geen kommersiële skaal hernubare elektrisiteit opgewek word nie.

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Table of Contents

Table of Figures

List of Tables

Nomenclature

Abbreviation	Meaning
$ or US$	United States Dollar
AEL	Atmospheric Emissions License
CAGR	Compound Annual Growth Rate
Cal	Calories
CMI	Construction, Manufacturing and Installation
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CSP	Concentrated Solar Power
EE	Energy Efficiency
EIA	Environmental Impact Assessment
ESKOM	Electricity supply commission of South Africa
FIT	Feed-in-tariff
GDP	Gross Domestic Product
GDPR	Regional Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
HDI	Human Development Index
HessREM	Hessequa Renewable Energy Model
HTF	Heat Transfer Fluid
IAP	Invasive Alien Plants
IDP	Integrated Development Plan
IEA	International Energy Agency
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
KPA	Key Performance Area
MSW	Municipal Solid Waste
NERSA	National Energy Regulator of South Africa
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
OECD	Organisation for Economic Co-operation and Development
PPA	Power Purchase Agreement
PPP	Public - Private Partnership
PV	Photovoltaics
R	South African Rand
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RET	Renewable Energy Technology
RoR	Run-of-river
SA	South Africa
SAEON	South African Environmental Observation Network
SAGEM	South African Green Economy Model

Abbreviation	Meaning
SDM	System Dynamics Model
SE4All	Sustainable Energy for All
STE	Solar Thermal Energy
TFEC	Total Final Energy Consumption
UNFCCC	United Nations Framework for Convention on Climate Change
USA	United States of America
WASA	Wind Atlas of South Africa
WeCaGEM	Western Cape Green Economy Model

CHAPTER 1: INTRODUCTION

1.1 The South African Electricity Context

South Africa is regarded as a developing country. The energy intensive economy is mainly supplied of electricity generated by Eskom, a state owned enterprise that also has a monopoly on the country's electricity sector. Eskom is responsible for approximately 95% of South Africa's electricity generation. The power utility has an installed generation capacity of 42.1 GW. This is composed of mostly coal-fired and nuclear power stations that account for 35.7 GW and 1.8 GW respectively (Eskom, 2015a).

Regardless of the power producer's size and installed capacity, the enterprise has struggled to supply power to South Africa since 2008. Due to a convergence of a number of factors including mass electrification of households, inadequate maximum load planning (Holm, 2009), and the strong economic growth in various industrial sectors in South Africa, the demand for electricity was greater than the supply. Coal could not be produced and delivered fast enough to keep up with demand. As a result, load shedding was implemented in 2008 (Fell, 2009). Other reasons for the lack of generating capacity was the lack of maintenance of many of the South African power plants, a lack of investment in new generation capacity since 1998, delayed decisions regarding the construction of the Medupi and Kusile power stations and the absence of a funding plan for Medupi and Kusile. Problems with inadequate geological surveys, skills shortages, boiler welding issues, labour unrest and strikes delayed construction of these projects even further (Ismail, 2014; Kenny, 2015). NERSA estimated the cost of the 2008 energy shortage at R 50 billion (Mail & Guardian, 2008). Prior to the energy crisis, the availability of comparatively cheap and abundant supplies of electricity has led to the available electricity being used inefficiently (Winkler, 2007). This may also have contributed to the energy shortage.

Due to an inadequate supply of electricity and the resulting constraints placed on the economy, South Africa's Department of Energy has attempted various strategies to expand current generating capacity. The Medupi and Kusile power stations (which are currently under construction), new nuclear power plants, IPP programmes, and additional oil and gas production programs (offshore and fracking) will all contribute towards more generating capacity (Hedden, 2015). Many believe that the best way forward is to focus on a mix of renewable energy capacity with storage and gas-turbine power generation. This will provide a more flexible energy system, best suited for dealing with an uncertain future regarding energy demand in South Africa (WWF, 2015; Wright, Bischof-niemz, Van Heerden & Mushwana, 2016)

For a short period these load shedding events were avoided through the commissioning of expensive diesel generation capacity. In 2014, Eskom suffered a furnace explosion, the collapse of a coal silo and the failure of an ash removal system at three different power stations (Kenny, 2015). Load shedding was again implemented that year. The resulting lack of energy security has had many negative effects on the country. In fact the entire economy has suffered from the unreliable supply of electricity. Stage 1 load shedding for 10 hours/day for 20 days a month was estimated to result in losses of R 20 billion per month. Using the same time scale of 10 hours/day for 20 days a month, stage 2 and stage 3 load shedding could have resulted in losses of R 40 billion per month and R 80 billion per month respectively (Van der Nest, 2015). National economic growth rates have slowed down, whilst international credit ratings from institutions such as Standard & Poor, and Fitch and Moody's have deteriorated (Strydom, 2015; Hogg, 2014; Donnelly, 2014; Booysen, 2014; Mdluli, 2014).

In 2015, Eskom (Electricity Supply Commission of South Africa) still had insufficient generating capacity to meet demand. Hedden (2015) stated that Eskom will most likely not be able to keep up with the growing demand in the future either. In order to meet peak demand, Open Cycle Gas Turbines (OCGTs) power plants that burn diesel fuel were employed. Koeberg's average electricity price at the time was approximately 70 cents/kWh, but the new gas turbine electricity generation cost more than R 3.20/kWh. The idea was to only run these plants for short periods during peak times when the load on the national grid was high. Unfortunately, they were used very frequently and for long time periods. The fuel cost alone was R 5 billion in 2013 and R 10.9 billion in 2014 (Kenny, 2015). To cover the additional costs, Eskom applied to NERSA (National Energy Regulator of South Africa) for electricity tariff increases (Hedden, 2015).

Renewable energy options were also considered by Eskom and government in an attempt to close the electricity supply-demand gap, but these prospects are no longer as promising as they once were. Various parties voiced their concern over Eskom's recent refusals to sign new Power Purchase Agreements (PPAs) with Independent Power Producers (IPPs) after the latest Renewable Energy Independent Power Producer Procurement Programme (REIPPP) bidding rounds. Such actions might discourage future investments from the private sector, and will also negatively impact the green economy in South Africa (Williams, 2016). In a news article, le Cordeur (2016a) stated that such actions by Eskom is not only against government policy, but also anti-competitive.

Eskom has managed to avoid load shedding for a couple of years now due to improved performance by state owned enterprise's power plants and the stagnated growth in electricity demand (le Cordeur, 2016b). As a result, the need for new renewable generation capacity is not as apparent as it was a few years ago. However, safety margins between electricity supply and demand are still well below the target of 15% (Eskom, 2016a).

Eskom's electricity prices have increased dramatically over the last decade and the cost of renewable energy technologies have decreased significantly. The net effect of Eskom's rising electricity price and the recent fall in renewable energy generation costs, is that stand-alone renewable energy generation capacity now competes with grid-supplied electricity. Hence, many South Africans have started to switch to off-grid renewable energy technologies to meet their energy demands. This a problem for many municipalities as they use profits from electricity resale to subsidise other service delivery activities. Their shrinking customer base is causing financial pressure and thus an inability to maintain service delivery levels. This nexus of issues is commonly referred to as the municipal dilemma and will be discussed in more detail later in this document.

The next section briefly discusses the South African policy and regulatory landscape regarding electricity generation. The current role of local government and its potential future role and responsibilities regarding electricity are also highlighted.

1.2 South Africa's Electricity Policy and Regulatory Landscape

The government system in South Africa consists of three tiers of government: 1) National Government, 2) Provincial Government, and 3) Local or Municipal Government. The municipal government is subjected to various policies, laws and regulations of the provincial government, which is in turn subjected to the policies, laws and regulations of the national government, which again is subject to the Constitution as the supreme act of the Republic of South Africa (Republic of South Africa, 1996). Therefore any national policy regarding renewable energy will have a cascading effect all the way down to the municipal level.

Since legislation on all levels will influence electricity provision (a municipal mandate), a basic understanding of the relevant legislation is required in order to address the municipal dilemma.

Some background knowledge on the legal jargon may be required for a better understanding of the context and legal frameworks around energy generation. Policies are not laws. They can be viewed as documents that highlight the requirement for new laws or the amendment of existing ones to achieve policy goals. Before policies can be signed off by the President and become Acts, they have to undergo a process of public comment and also have to be aligned with existing acts. That act is then enforceable by law. The process can be a long one due to delays, areas of conflict, enforcing and then revising the acts (Tshehla, 2014).

1.2.1 Energy and electricity policies and the regulatory environment

The Constitution of the Republic of South Africa, which is the supreme law of the country (Republic of South Africa, 1996), states the following:

"Everyone has the right –

a) to an environment that is not harmful to their health or well-being; and
b) to have the environment protected, for the benefit of the present and future generations, through reasonable legislative and other measures that –
    i. prevent pollution and ecological degradation;
    ii. promote conservation; and
    iii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development".

Since most of South Africa's electricity is derived from fossil fuels, it could be argued that even the Constitution demands investment in RETs, or at least that policies regarding energy should be guided by it. Furthermore, the Constitution's Section 152(1)(b) and Section 152(1)(d) respectively states that sustainable community service provision and the promotion of a safe and healthy environment as objectives of local government. Section 153 requires local government to be developmental-orientated. Considering these matters in regards to renewable energy, as well as energy efficiency (EE), one could argue that RE and EE is not only a competency of local government, but a responsibility as well (Brent, Douglas, Mosdell & Scheepers, 2015).

All statutory bodies or functionaries of state are bound by the environmental management principles outlined in the National Environmental Management Act No.107 of 1998. These principles apply to municipalities as well. Relating to renewable energy, Section 2(3) and Section 2(4)(a) respectively require development to be socially, environmentally and economically sustainable, and that pollution and environmental degradation should be avoided (Republic of South Africa, 1998). The Act also includes regulations regarding environmental authorisation. RE projects that aim to install generating capacities from 10 to 20 MW will potentially trigger environmental authorisation. When the projects aim for capacities exceeding 20 MW, a full scoping and environmental impact assessment (EIA) will be required.

The Electricity Regulation Act of 2006 states promotion of diverse energy sources and energy efficiency, as well as facilitation of investment in the electricity supply industry, as objectives (Republic of South Africa, 2006a). The National Energy Act No. 34 of 2008 states as its goal: "To ensure that diverse energy resources are available, in sustainable quantities and at affordable prices, to the South African economy in support of economic growth and poverty alleviation…" (Republic of South Africa, 2008). These Acts support the notion that renewable energy is a priority for government, on paper at least.

The National Energy Regulator of South Africa (NERSA) was established through the National Energy Regulator Act No. 40 of 2004 (Republic of South Africa, 2004). NERSA is the licensing authority for all electricity generation activities (RE included). It is important to note that these licenses issued by NERSA are open ended. That means that NERSA can impose any additional conditions at its discretion. NERSA is also empowered by the Electricity Regulation Act No.4 of 2006 to regulate electricity tariffs. Matters regarding licensing around electricity and electricity generation are dealt with in the Electricity Regulation Act No.4 of 2006. Section 8 of the Act states the following (Republic of South Africa, 2006a):
"8(1) No person may, without a license issued by the Regulator in accordance with this Act –

(a) operate any generation, transmission or distribution facility;
(b) import or export electricity; or
(c) be involved in trading."

However, Schedule II activities, do not have to apply for a license. Such activities include electricity generation for own use or generation that is not grid connected. Although a distribution and trading license would still be required, municipalities with RE installations might in some cases not require a generation license if only local electricity consumers are serviced and the facility is not connected to the national grid.

Other Acts that might be applicable include the Municipal Systems Act No.32 of 2000 and the Municipal Finance Management Act No.56 of 2003. Sections 25 and 26 of the Municipal Systems Act contain guidelines and the core components for integrated development plans (IDPs) for municipalities. Municipalities are obligated to follow these policy instruments. Within the IDPs must be reflected the aspirations and needs of the communities for which they were created. Furthermore, these documents create obligations and expectations for the local governments and the communities respectively. They also guide resource allocation and set development priorities (Brent *et al.*, 2015). Referring back to Sections 25 and 26 of the Municipal Systems Act, Brent et al. (2015) conclude that municipalities are required to do planning guided by the concepts of sustainable development, provide for sustainable service delivery, as well as ensuring local economic development. Sections 77 and 78 of the Municipal Systems Act contain information on the processes that need to be followed when municipalities want to upgrade, extend or improve their services. The Municipal Finance Management Act contains guidelines for the procurement of goods and services in municipalities (Republic of South Africa, 2006b). These Acts should thus be consulted when RE projects are being considered.

South Africa has a range of other policy documents that support the use of renewable energy. The first major document was probably the 2003 White Paper on Renewable Energy that set the target of 10 000 GWh from RE for South Africa by 2013 (Department of Minerals and Energy, 2003). Other documents that support expanding South Africa's renewable energy capacity and diversifying the country's energy mix include the following:

- **National Climate Change Response White Paper (2011):** The paper mentions the Renewable Energy Flagship Programme that aims to scale up the RE programme as stipulated in the 2010 IRP. The South African Renewables Initiative, which aims to act as a driver for RET deployment and enhancing local manufacturing, is also highlighted (Republic of South Africa, 2011).
- **National Development Plan (2012):** This document states that over 20 000 MW of RE should be installed before 2030. Along with this, 11 000 MW of aging coal power capacity will be decommissioned. However, it was estimated that 40 000 MW of new generating capacity will be required to meet the country's electrification targets (National Planning Commission, 2012).
- **Integrated Resource Plan (2010 – 2030):** The IRP serves as a policy instrument that can aid in planning for the country's future electricity capacity. The document sets a target of 17.6 GW of wind power and 11.3 GW of solar power (Department of Energy, 2013).
- **Integrated Resource Plan (2010 - 2030) 2016 Update:** The Integrated Resource Plan (IRP) should be updated regularly as new electricity demand data, economic data and technology costs become available. Various previous versions of the IRP (2010 – 2030) were criticised in the past. This one was no different as many appendices containing assumptions used in the

IRP were omitted, outdated exchange rates were used, technology costs were incorrect and inconsistent, many of the expenses surrounding nuclear power technology were ignored, arbitrary constraints were placed on the annual delivery of renewable energy technologies and many other issues were also highlighted (Republic of South Africa - Department of Energy, 2016; Yelland, 2016).

- Other documents that address the need for renewable energy and related topics include the Green Economy Accord, and the New Growth Path Framework.

It is again clear from the above mentioned documents that promoting renewable energy and the diversification of South Africa's energy mix in general is considered a high priority.

1.2.2 General recommendations regarding municipal renewable energy policies

Mutingi (2013) investigated the dynamics of RET (renewable energy technology) adoption and points out a number of managerial insights that are essential for renewable energy policy-makers:

- Promotional efforts are a major driving force for adopting RET, and thus considerable effort should be put into marketing (advertising, campaigns and promotional initiatives) of these technologies.
- Teaching and training initiatives, as well as word of mouth, will contribute to promotional initiatives.
- Reducing constraints and barriers related to RET (e.g. RET costs) will improve adoption.
- Speeding up the RET adoption process will require financial aid and support services.

Kaggwa (2013) hypothesises that if a holistic approach, that includes a social dimension, is not followed with policy articulation (the focus is on bio-energy) then there would be a high likelihood of such policies being ineffective. The application of systems thinking is suggested as a means to mitigate resistance against these energy policies.

Tshehla (2014) argues that municipalities that seek to implement a bottom-up approach to grow renewable energy could assist in the following ways:

- The local government should seek clarity on regulations.
- They should write by-laws that encourage RET implementation.
- They need to be proactive in their engagement with national government about facilitation of RE generation and RET adoption at a local level.

Insights from these individuals should be taken into account when planning RET implementation strategies.

1.3 Rationale for the Study

South Africa as a country has an obligation to mitigate climate change as signatory of the Kyoto Protocol and United Nations Framework for Convention on Climate Change (UNFCCC). South Africa has submitted an intended nationally determined contribution on adaptation, mitigation, finance and investment to combat climate change. Among other things, it indicates that the country has made a transition in its commitment to mitigating climate change. In the past the commitment was only to slightly deviate from business-as-usual, but that has now changed to a situation where South Africa is committed to an absolute peak, plateau and reduction in greenhouse gas (GHG) emissions (UNFCCC, 2015). One approach to fulfil this obligation is investing in RET to decrease carbon emissions, as highlighted in the Western Cape's Green Economy Strategy Framework (Western Cape Government, 2013a). This problem should be addressed on all levels (internationally, national, provincial and local municipal level as well).

On a local level, municipalities often fail to invest in RETs due to financial risks involved in the process. Policies and regulations regarding electricity generation and distribution are also ambiguous (Tshehla, 2014). Considering the fact that many municipalities rely heavily on revenue generated from electricity sales to finance the delivery of other services, it is understandable that the risks seem too great in most cases. For example, Hessequa received 29.73% of its income from the sale of electricity in 2015 (Grant, 2015). As the price of electricity has increased significantly during the last decade (and is likely to continue rising), total revenue from electricity sales will likely be reduced as consumers invest more aggressively in private RETs. Due to their falling capital costs these technologies have become more economically attractive. The downside for municipalities is that service delivery might start to decline due to reduced electricity revenue. To counteract the reduction in electricity revenue, municipalities increase the selling price of electricity even more. On the one hand this does increase revenue, but it also leads to more people defecting from the local electricity grid. Thus the municipal customer base continues to shrink. This interconnected network is commonly referred to as the "municipal dilemma" and is illustrated in Figure 1.

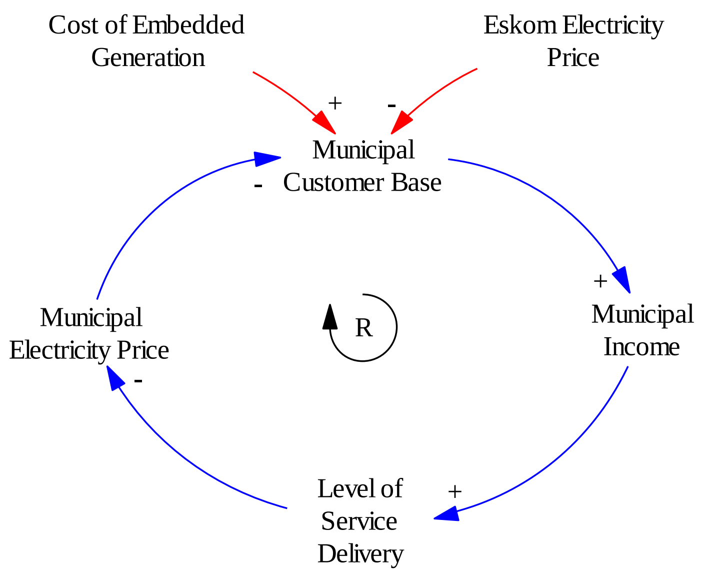

Figure 1: Causal loop diagram of the municipal dilemma

However, there are opportunities for municipalities to invest in renewable energy technology. Among others, the provision of services such as water, energy, basic accommodation, safety and health are included in municipal mandates (Republic of South Africa, 1996). Thus, the rationale for conducting this study is to find a way to expand the RE generating capacity within Hessequa municipality in a balanced manner, in order to address the municipal dilemma.

1.4 Research Problem and Research Question

Hessequa Municipality and the School of Public Leadership at Stellenbosch University signed a memorandum of understanding according to which these parties would participate in the socio-economic development of the Hessequa region. On 10 March 2015, an idea generation session was held in the main town Riversdale, to discuss different strategies and ideas to stimulate socio-economic development of the Hessequa region. The possibility of a biomass power plant to convert the region's large reserves of invasive alien plants into electricity was raised. This idea was discussed further during an energy summit held in the town of Stillbaai on 23 and 24 July 2015. The goal of the energy summit was to explore alternative ways to reduce the dependency of the municipality on grid-supplied electricity, through the development of alternative sources of renewable energy.

During the summit various challenges and problem areas were identified. The five highest priority challenges, or areas that require attention, are the following (in order of priority):

1 Determining the appropriate electric energy supply options for Hessequa. The energy conversion technology has to be technologically proven, reliable, available, and accessible.

2 Understanding the demand side of the energy equation and finding ways to reduce or optimise peak demand from the grid.

3 The impact of the supply of renewable energy as a substitute for grid electricity on the municipal account (due to a reduction in conventional electricity sales). The model used for tariffs and revenue modelling has to be revised to determine the effects of reduced revenue, cross-subsidies, and the capital required to pay for the renewable energy projects.

4 Social responsibility as a key consideration in the local energy sector. All stakeholders have to be involved in decision-making regarding renewable energy projects, especially the affected communities. The community needs to be educated and made aware of the possibilities and advantages of renewable energy. Communities have to take co-accountability for the success of any renewable energy projects, and private-public partnerships involving the community have to be established.

5 Energy is required for sustainable economic growth and social development. Green (renewable) energy should be used to promote such economic growth.

Hessequa Municipality decided to investigate the possibility of investing in renewable energy technology to increase energy security in the Municipality and (potentially) to stimulate the local economy in the process. The aim of this study is then to address the highest priority challenge identified at the energy summit, namely: *determining an appropriate combination of electric energy supply options for Hessequa*. This study would in part pave the way for future work and assist in designing a road map for future action while also addressing the challenges associated with the municipal dilemma to some extent. Against the above background the research question for this study is formulated as follows:

> *What is the appropriate combination of renewable energy supply options for the Hessequa Municipality?*

The following three research sub-questions are formulated to address the main research question:

1. Which renewable energy technologies could be considered for the generation of future supplies of renewable electricity within the context of the Hessequa Municipality?
2. What are the nature and features of a dynamic quantitative model that can be used to determine an appropriate and sustainable electric energy supply mix to the Hessequa Municipality up to the year 2040?

3. What policy options would result in implementing the most appropriate mix of renewable energy technologies in terms of various sets of desired impacts on the economy, society and the environment?

In order to address the research question and the related research sub-questions a number of research objectives are set for the study.

1.5 Research Objectives

The following specific research objectives are addressed in this study in response to the research questions:

- To review the current renewable energy technologies that could be considered for supplying renewable electric energy to the Hessequa Municipality, given the municipal context.
- To develop a dynamic model that can be used to determine an appropriate and sustainable electric energy supply mix in terms of different sets of socio-economic and environmental objectives.
- To find policy options that would contribute to the most appropriate renewable electric energy supply mix in terms of different sets of desired outcomes for the economy, society and environment of the municipal area.

1.6 Research Strategy and Methodology

The study is conducted in three phases, corresponding to the three research objectives:

- Phase 1:
    - Conduct a literature review (in Chapter 2) to determine which proven and relevant technologies are available for renewable energy electricity generation within the Hessequa municipal area.
    - Undertake an electricity audit of the Hessequa area to understand the basic characteristics of the current electricity supply and demand system as a reference point, for future development (audit results appear in Chapter 3 and Appendix F).
    - Evaluate the availability of renewable energy resources in the municipal area that can be used for electricity generation (see Appendix E).

- Phase 2:
    - Evaluate different modelling approaches and methods and select an appropriate method as a planning tool for Hessequa's renewable electricity future (see Chapter 2).
    - Developed a dynamic model to simulate the dynamic interactions between the electricity supply side, the different sectors on the demand side, and contextual variables that affect both supply and demand of electricity within the Hessequa municipal area up to the year 2040 (see Chapter 4).
    - Investigate the effects of the implementation of a mix of renewable electricity generating technologies for Hessequa over time, to determine the most appropriate electric energy supply subject to relevant constraints (see Chapters 5).
- Phase 3:
    - Investigate policy options to encourage the installation of renewable energy generating capacity in Hessequa in order to assist in setting appropriate energy targets, and evaluate the likelihood of achieving these targets (see Chapter 5).

The next chapter contains the literature review that covers the renewable energy technologies that can be considered for implementation within the context of the Hessequa Municipality and the various models that could be considered for the purposes of this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to the Literature Review

The purpose of this chapter is to address the first research objective for this study which is to review the various renewable energy technologies currently available that can be considered as technology solutions for the long term electricity strategy of the Hessequa Municipality. This chapter also addresses a part of the second research objective, namely to find an appropriate quantitative, dynamic modelling approach and tool that can be used to address the third research objective of finding a certain renewable energy mix for the Hessequa Municipality over time.

The South African electricity sector as well as the regulations regarding the electricity industry have already been discussed in chapter one. The literature review will focus mainly on the different types of renewable energy technologies (RETs) currently available. Being one of the main objectives of this study, it is important to understand the characteristics of each technology. The general environmental and socio-economic benefits of renewable energy will also be discussed. The goal of these sections are to further support the case for RETs as well as highlight the potential challenges. Finally, various modelling methods are evaluated to determine the most appropriate modelling method for assisting Hessequa in planning its renewable energy futures.

2.2 Renewable Energy Technologies

One of the most widely accepted definitions of renewable energy is that of the International Renewable Energy Agency (IRENA): "*Renewable energy includes all forms of energy produced from renewable sources in a sustainable manner, including bioenergy, geo- thermal energy, hydropower, ocean energy, solar energy and wind energy*" (World Bank, 2013a: 194).

Other definitions also exist, but most of these require renewable sources to be sustainable. Biomass is occasionally the exception to this due to inadequate data to determine if it is used in a sustainable manner. The lack of international sustainability criteria for major renewable energy technologies (RETs) further complicates the distinction between sustainable and unsustainable technologies (World Bank, 2013a).

Due to high maintenance costs and intermittency, many RETs have not been economically competitive with more traditional electricity generation methods (Manzano-agugliaro, Montoya, Gil, Alcayde, Gómez & Ba, 2011). In recent years the situation has changed, and many RETs have become competitive with fossil fuels, especially solar and wind power.

Tables 1 and 2 summarise the basic characteristics and costs associated with each technology. Table 3 presents more information on the various renewable energy technologies, but focuses on developing countries. For overviews of the various generation methods refer to Appendix B.

Table 1: Characteristics of renewable energy technologies - part 1. Source: REN21 (2015)

Typical Characteristics	**Capital costs** (US$/kW)	**Typical Energy Costs** (LCOE - US cents/kWh)
Bio-power (Solid biomass, co-firing, organic municipal solid waste)		
Plant size: 0.5 - 200 MW Conversion efficiency: 25 - 35% Capacity factor: 25 - 95%	800 - 4500 (Global) 200 - 1000 (Co-fire)	3 - 22 (Global) Co-fire: 4 - 14 (Global)
Bio-power (gasification)		
Plant size: 0.03 - 40 MW Conversion efficiency: 30 - 40% Capacity factor: 40 - 80%	2050 - 5500 (Global)	6 - 24 (Global)
Bio-power (Anaerobic digestion)		
Plant size: 0.075 - 20 MW Conversion efficiency: 25 - 40% Capacity factor: 50 - 90%	Biogas: 500 - 6500 Landfill: 1900 - 2200	Bio-gas: 6 - 19 Landfill: 4 - 6.5
Geothermal Power		
Plant size: 1 - 100 MW Capacity factor: 60 - 90%	Condensing flash: 1900 - 3800 Binary: 2250 - 5500	Condensing flash: 4 -14 Binary: 7 - 24
Hydropower (Grid based)		
Plant size: 1 MW - multi GW Plant type: reservoir, RoR Capacity factor: 20 - 80%	Projects ≥ 20MW: 750 - 2500 Projects ≤ 20 MW: 750 - 4000	Projects ≥ 20MW: 2 - 8 Projects ≤ 20MW: 3 - 23
Ocean Power (Tidal range)		
Plant size: <1 to >250 MW Capacity factor: 23 - 29%	5290 - 5870 (Global)	21 - 28 (Global) 35 - 42 (Europe)

Table 2: Characteristics of renewable energy technologies - part 2. Source: REN21 (2015)

Solar PV (Rooftop PV)		
Peak capacity: 3 - 5 kW (Residential) 100 kW (Commercial) 500 kW (Industrial) Capacity factor: 10 - 25% (Fixed tilt)	**Residential costs:** 2200 (Germany) 3500 - 7000 (USA) 4260 (Japan) 2150 (China) 3380 (Australia) 2400 - 3000 (Italy) **Commercial costs:** 3800 (USA) 2900 - 3800 (Japan)	21 - 44 (OECD) 28 - 55 (Non-OECD) 16 - 38 (Europe)
Solar PV (Ground-mounted utility scale)		
Peak capacity: > 1 - 250+ MW Capacity factor: 10 - 25% (Fixed tilt)	1200 - 3000 (Global) Weighted capital costs (2014): 1670 (China) 2710 (Japan) 1495 (Germany) 2080 (United Kingdom) 2218 (USA) Concentrating PV (CPV): 1480 - 2330 (10MW)	10 - 38 (OECD) 7 - 40 (Non-OECD) 14 - 34 (Europe) 11 (China) 25 (Japan) 11 (USA)
Concentrating solar power (CSP)		
Types: parabolic trough, tower, dish **Plant size:** 50 -250 MW (Trough) 20 - 250 MW (Tower) 10 - 100 MW (Dish) **Capacity factor:** 20 - 35% (No storage) 35 - 80% (With storage)	**Trough, no storage:** 5000 - 7000 (OECD) 3100 - 4050 (Non-OECD) Trough, 6 hour storage: 6000 - 8000 **Tower:** 6000 (USA without storage) 9000 (USA with storage)	**Trough and Fresnel:** 19 - 38 (No storage) 17 - 37 (6 hour storage) **Tower:** 12.5 - 16.4 (USA) high end of range is with storage
Wind (Large onshore)		
Turbine size: 1.5 - 3.5 MW Capacity factor: 20 - 50%	925 - 1470 (India) 660 - 1290 (China) 2300 - 10000 (USA) 5873 (UK)	4 - 16 (Global) 6 - 7 (Asia, Eurasia, North America) 5 - 10 (Central and South America)
Wind (Small onshore)		
Turbine size: up to 100 kW Average: 0.85 kW (Global) 0.5 kW (China) 1.4 kW (USA) 4.7 kW (UK)	2300 - 10000 (USA) 1900 (China) 5870 (UK)	15 - 20 (USA)
Wind (Offshore)		
Turbine size: 1.5 - 7.5 MW Capacity Factor: 35 - 45%	4500 - 5500 (Global) 2250 - 6250 (OECD)	15 - 23 (Global)

Table 3: Characteristics of renewable energy technologies – part 3 Source: REN21 (2015)

	Characteristics	**Costs (Capital or LOCE) ($/kW or US cents/kWh)**
Biogas digester	Digester: 6 - 8 m^3	Unit Cost: $ 612 / Unit (Asia); $ 886/ Unit (Africa)
Biomass gasifier	Size: 20 - 5000 kW	LCOE: 8 - 12 (Global) LCOE: 5 - 6 (China)
Solar home system	System size: 20 - 100 W	LCOE: 160 - 200 (Global) LCOE: 4 (Bangladesh)
Household wind turbine	Turbine size: 0.1 - 3 kW (off-grid residential) 1.1 - 2.5 MW (Industrial, institutional)	Capital Costs : 10000/ kW (1 kW turbine) 5000 / kW (5 kW turbine) 2500 - 3500 / kW (250 kW turbine) LCOE: 15 - 35+
Hydropower	Plant size: 0.1 - 1000 kW Plant/storage type: RoR, diurnal storage, hydrokinetic System size: 10 - 1000 kW	Capital cost: 1175 - 6000 LCOE: 5 - 40

2.3 Renewable Energy Benefits

Aside from potentially making the world less reliant on fossil fuels, renewable energy has multiple benefits, both environmental and socio-economic. This section will briefly discuss some of these benefits.

2.3.1 Socio-economic benefits of renewable energy

Installing renewable electricity generating capacity in an area supports diversifying its economy. Diversification benefits an economy by increasing the possible ways to generate revenue. More spin-off benefits are added when workers who benefitted from RE start spending their earnings in the local economy.

When a town, for instance, generates more electricity than it uses the surplus power may be fed back into the grid at a feed-in tariff. Wildpoldsried in Germany is one example of such a town (Moore, 2011). To duplicate this performance might be difficult, given the current South African regulatory framework and Eskom's dominance as a monopolistic player in the South African electricity sector.

Social benefits mentioned by Akella, Saini and Sharma (2009) include diverse energy options for consumers, improved citizen health and greater energy self-reliance. Work opportunities associated with construction, maintenance and operation of energy systems can also be counted among the benefits of a renewable energy industry.

Occasionally the transition to greener energy systems might be inconvenient for some groups. Modern biomass energy has the potential to not only increase the availability of clean energy, but might also lead to unemployment of rural people who produce rudimentary biomass energy products such as fire wood (Kaggwa, 2013). The benefits of bio-energy may in some instances only benefit the middle class and affluent segments of society. In addition to these socio-economic benefits a number of environmental benefits are also associated with RETs.

2.3.2 Environmental benefits of renewable energy

One of the largest global drivers for RET implementation is climate change and the need to reduce fossil fuel emissions such as carbon dioxide, nitrogen oxide, methane and sulphur dioxide. Almost all renewable energy sources have no direct CO_2 emissions, except biomass. Biomass power can however be considered a carbon neutral process in many cases. For example, emission released during biomass combustion would eventually have been released during the biomass' decomposition (this does not account for emissions related to transport and other processing emissions). Table 4 presents the direct and indirect emissions associated with different energy technologies.

Table 4: Emissions of CO_2 and methane associated with electricity generation technologies. Source: IPCC (2014)

Technology	**Direct emissions (gCO2eq/kWh)**	**Infrastructure and supply chain emissions**	**Methane emissions**	**Lifecycle emissions (gCO2eq/kWh)**
	Min/median/max	Typical values		Min/median/max
Coal	670/760/870	9.6	47	740/820/910
Gas	350/370/490	1.6	91	410/490/650
Biomass	N/A	210	0	130/230/420
Geothermal	0	45	0	6/38/79
Hydropower	0	19	88	1/24/2200
Nuclear	0	18	0	3.7/12/110
CSP	0	29	0	8.8/27/63
Rooftop PV	0	42	0	26/41/60
Utility PV	0	66	0	18/48/180
Wind	0	15	0	7/11/56

Even though technologies such as solar power and wind power have no direct emissions in their electricity production processes, potentially dangerous compounds are used during the manufacturing of their components (Union of Concerned Scientists, 2013).

Reductions in air pollution and greenhouse gas emissions, long-term preservation of natural resources and a reduction in energy resource transportation are also considered benefits of renewable energy (Akella *et al.*, 2009). In the case of biomass, water security may be improved if invasive alien plants are used as feedstock for power plants, especially in water scares areas.

2.4 Barriers to Renewable Energy and Electricity Progress

Barriers to the adoption of renewable energy technologies can be technical or non-technical. Some of these barriers are related to policies and institutions, financing, economics, capacity, information or other aspects of RE (Brent & Amigun, 2009). Holm (2009) argues that an outdated mind-set on supply side management, partial energy costing, short-term thinking that favours lower initial costs for energy projects and a low energy price due to subsidies, are some of the notable constraints for South African RE development. Challenges highlighted by Painuly (2001) include market related barriers, institutional, social, technical, environmental, and political barriers. Painuly also mentions additional barriers like the availability of resources, technology and skills. He further indicates and many of these barriers may be specific to a certain technology, country or region. However, the main constraint RET implementation is often a lack of motivation and political will (Holm, 2009). Many of the general issues, challenges and barriers to widespread development in renewable energy are applicable at local governance level (Tshehla, 2014), and thus also apply to the Hessequa Municipality. The mentioned barriers, challenges and issues often manifest in an interlinked manner. Tshehla (2014) therefore used the notion of a “system of barriers” to discuss possibilities of overcoming RET implementation barriers at municipal level. To identify possible barriers to RET, Painuly (2001) recommends literature surveys of similar projects, site visits to the areas under consideration, and interactions with stakeholders.

2.5 Renewable Energy Technology Evaluation

The initial technology selection criteria included capital cost, renewable resource availability, technology maturity and other technically limiting factors. Table 5 provides a summary of the performance of each technology. Those that are considered to be suitable for deployment in Hessequa are highlighted in green in the "Overall suitability" column. CSP is considered to be too expensive (approximately R 89 mil/MW based on the 3rd REIPPPP bidding round (Eberhard, Leigland & Kolker, 2014) and not mature enough due to the relatively low global installed capacity (4.4 GW (REN21, 2015)). CSP is also better suited for areas like the Northern Cape with year round sunshine. Winter rainfall and relatively low ambient temperatures in the Western Cape limit CSP as a renewable energy technology for Hessequa. Since no geothermal power has received attention during the REIPPPP bidding windows, no local data regarding capital cost for this technology was available. Internationally geothermal power capital costs range from 1900 – 5500 US$/kW, depending on the technology used (REN21, 2015). This is more expensive than solar PV and wind power in most cases. Although geothermal power is not new, the global generation capacity is only 12.8 GW (REN21, 2015), making the technology appear less mature. A major technical or resource availability constraint is that there are no known viable sites in Hessequa for geothermal power generation. Ocean power is still in its infancy with a global generation capacity of 0.5 GW. Capital costs for these projects range from 5290 – 5870 US$/kW (REN21, 2015). The technology is still new and there are many issues with logistics as well as maintenance because of the harsh environment that equipment is exposed to. Landfill power was considered to be unviable due to Hessequa's low waste generation and the lack of a central landfill site. Most of the towns in Hessequa have their own landfill site. Couth, Trois, Parkin, Strachan, Gilder and Wright (2011) state that power generation is usually not viable for small to medium sized landfills (receiving 500 – 1000 tonnes of waste a day). Landfill power generation was thus ruled out for this study. Based on the evaluation criteria in Table 5, only solar PV, wind power, biomass power and pumped storage (hydropower) are likely to be viable RETs in the Hessequa area.

Table 5: Renewable energy technology selection

Technology	Capital cost	LCOE	Resource availability	Technology maturity (based on installed capacity)	Limiting technical constraints	Overall suitability
Solar PV	X	X	X	X	X	X
CSP			X			
Wind	X	X	X	X	X	X
Biomass	X	X	X	X	X	X
Geothermal		X		X		
Ocean power			X			
Hydro	X	X	X	X	X	X
Landfill	X	X		X	X	

2.6 Modelling Methods Overview

Models are standard tools used for energy planning (Jebaraj & Iniyan, 2006). When looking at energy and electricity, it should be considered in the context of the larger system. Changes in other factors and sectors like economics, population, education, health, agriculture, water, infrastructure and government spending will all have an impact on the energy sector, which in turn will impact everything else (Hedden, 2015). To effectively plan interventions in a system and determine likely outcomes of these interventions, a modelling tool is required. This section will review selected modelling methods and determine if any of the methods are appropriate for modelling the outcomes of interventions in Hessequa's electricity sector.

Modelling tools are particularly useful for policy analysis. In the case of Hessequa Municipality, energy security is not the only concern. Local government is also determined to drive green economic development. Central to this is sustainability. Therefore, it is important to select a modelling method that can capture the three pillars of sustainability (economic-, environmental- and social aspects) when policies regarding renewable energy are tested.

A main objective of this study is to estimate the outcomes of renewable energy investments over time. This requires the modelling method to capture the interactions of the economy, society and environment as well as their dynamic nature. Bassi (2014) conducted a comparative assessment of simulation models used in green economy policy making. His analysis includes econometrics, optimisation and simulation. This section discusses these three approaches, and evaluates their suitability to assess a sustainable electricity mix in Hessequa. Based on the evaluation, the most appropriate method is selected.

2.6.1 Econometrics

Schmidt (2005:5) defines econometrics as follows: "*Econometrics is the study of the application of statistical methods to economic problems.*" Although this definition is limited to economic theory, the principles can be applied in a more general sense. Bassi (2014) defines econometrics as measuring relationships between two or more variables, statistically analysing historical data and finding correlations between the variables being investigated.

Econometrics usually involves three stages: specification, estimation and forecasting. Through each of these stages, mathematics and statistical methods are applied to economic theory. One of the most common tools employed in econometrics is linear regression. It allows one to estimate the impact of changing one variable (the explanatory variable) on another variable (the dependent variable), while all other determinants of the dependent variable are taken into account (Ouliaris, 2011).

The benefits of this method are that it can deliver quantitative estimates, predictions and forecasts. Obstacles or limitations regarding econometrics often involve data. As with all computing problems, garbage in will result in garbage out. Other limitations relate to general assumptions in many economic theories, namely: that human behaviour can be fully rationalised, market equilibrium and the availability of perfect data (Bassi, 2014). Bassi (2014) further stated that validation of projections may be challenging and that forecasts can be unreliable due to that fact they are based on exogenous assumptions and historical data.

2.6.2 Optimisation

Mathematically, optimisation attempts to minimize or maximise the value of a function by varying inputs that are subject to constraints (Pardalos & Resende, 2002). Certain characteristics of the problem could however lead to the "optimal" solution not being feasible. Regarding the Hessequa electricity sector's context it should be noted that Weijermars et al. (2012) agreed with Pardalos and Resende (2002) that energy mix decisions can be guided by theoretical optimisation, but that these optimised solutions from a physical system's perspective might not always be optimal when the political and social context is considered.

Other problems in optimisation include calculation times that are too long for practical purposes. This gave rise to heuristic methods and artificial neural network methods as alternatives to conventional optimisation methods such as linear programming and, Lagrangian relaxation, Nelder-Mead Simplex method and quadratic programming. Solutions found to optimisation problems may not always be optimal, but are satisfactory in most cases (Manzano-agugliaro *et al.*, 2011).

Bassi (2014) highlights a number of challenges associated with optimisation modelling methods. These include defining the objective function correctly, feedback and dynamics are limited and there is extensive use of linearity. Exogenous variables like economic growth rates and population are also often used in these models. Another drawback is that optimisation does not usually provide forecasts, only snap-shots of the system's optimal state for specific time intervals.

2.6.3 Simulation

Ören (2011) created a list of 100 definitions for simulation. In simple terms, simulation modelling focuses on imitating the operation of a real-world system. It involves the creation of scenarios and projections into the future. The goal is usually to investigate possible outcomes of "what-if" questions in a quantitative manner.

According to Dooley (2002), there are three main sub-categories of simulation modelling: discrete event simulation, agent based modelling and system dynamics modelling. These methods can be summarised as follows:

Agent based modelling: These models function on an agent level and highlights emergence and self-organising patterns in complex systems. Agent based modelling follows a bottom-up approach. The individual agents as well as their patterns of connectivity are described, but the larger aggregate system's behaviour might not be known.

Discrete event simulation: This method can be described as modelling a system's operation as a discrete sequence of events in time. It is assumed that no change occurs in the system between these discrete events. Discrete event simulations are best suited for systems where variables and events change in a rule-oriented manner. Dooley (2002) states that this method is not suitable when entities and their internal mechanisms are more important elements of the simulation than events.

System dynamics modelling: The aim of system dynamics modelling is to understand the main drivers of behavioural change in a system. To accomplish this, properties of the real system such as feedback loops, delays, and non-linear interactions are identified and analysed using causal relationships (Sterman, 2000). System dynamics is different from discrete event simulation and agent based modelling because it follows a top-down approach. Therefore, extensive knowledge is required regarding the interactions between system elements.

Benefits of system dynamics modelling include the fact that it can provide a means to express the feedbacks and complex relationships in a system of interrelated activities and processes. Its usefulness is also demonstrated in facilitating policy intervention in complex systems by offering insight into potential outcomes of these interventions (Kaggwa, 2013). System dynamics can be used over any spatial or time scale (Sterman, 2000). Bassi (2014) stated that system dynamics can also provide flexibility, which can be convenient and relevant in all the stages of policy development. He indicates that correct system boundary definitions and identifying the correct causal relationships are some of the challenges associated with simulation type models.

2.6.4 Modelling methods evaluation

Selected modelling approaches are reviewed below and some of the issues and benefits of each are considered. As stated, the objective of this study is to create a modelling tool to assist the Hessequa Municipality in planning its renewable energy future. This tool must allow for policy testing, and according to Bassi (2014), an appropriate methodology must be selected to enable this.

When selecting the best modelling method it is important to consider the audience for which the model is being developed. The primary user of the model will most likely be local government officials, who will use it for policy testing. The policies will have a direct impact on Hessequa's electricity sector, which in turn will have social, economic and environmental impacts. A modelling method that is capable of identifying points of intervention or leverage points in the system will be required. This way, the maximum benefit can be obtained from interventions. The modelling method must be able to produce future projections and allow for trend evaluations. In most cases, policies can be more successful when they have public support. In Hessequa this requires public participation in the form of stakeholder engagement sessions. If the model can be explained in simple terms and the general public is able to understand the benefits of the suggested interventions, it is likely that interventions will have more support.

The different modelling approaches are thus evaluated based on the following criteria:

- Transparency.
- Flexibility.
- Ability to capture complex dynamic behaviour.
- Presentation of temporal behaviour.
- Accuracy of model results.

The results of the evaluation are presented in Table 6.

Table 6: Modelling method evaluation

Method	Endogenous variable representation (transparency)	Flexibility	Complex dynamics representation	Representation of temporal behaviour	Accuracy	Overall suitability
Econometrics				X		
Optimisation			X		X	
Simulation						
Agent based modelling	X	X		X		
Discrete Event Simulation	X			X		
System Dynamics	X	X	X	X	X	X

Based on the evaluation in Table 6, only system dynamics (simulation type modelling) fulfils all the criteria. Bassi (2014) indicates that system dynamics is generally more accessible for stakeholder participation, whereas econometrics and optimisation typically target a very specific audience. System dynamics can also incorporate knowledge into a single framework of analysis and it can be combined with other approaches. It should also be noted that neither optimisation nor econometrics are able to incorporate feedback loops; a central element to all complex systems. Furthermore, optimisation is unable to identify drivers of change in a system. Given the different strengths and weaknesses of the different modelling methods, system dynamics is selected as the most appropriate for achieving the objectives of this study.

Other studies that also use system dynamics modelling in the energy or electricity sector in the South African context include SAGEM (UNEP, 2013; Musango, Brent & Bassi, 2014; Musango, Brent & Tshangela, 2014) and WeCaGEM (Oosthuizen, 2016; Oosthuizen, Brent, Musango & de Kock, 2016). For more details regarding the methodology of system dynamics, see Appendix C.

2.7 Literature Review Summary

The various renewable energy technologies were briefly discussed and compared in terms of their general characteristics, capital cost and levelised cost of electricity. This chapter served as an introduction to the various technologies. More detail about specific RETs are available in Appendix B. The conclusion of the review of the different RETs is that the more appropriate technologies to implement within the Hessequa context are the following (in no specific order of relevance):

- Biomass RETs
- Solar PV technology
- Wind power technology
- Hydro power as pumped storage

Regarding the benefits of renewable energy, the discussion focused on socio-economic and environmental benefits. A major socio-economic benefit of renewable energy is job creation during the planning and construction phase and also during the operation phase of such a facility. In either case, expanding an area's renewable energy capacity can support job creation. The discussion on environmental benefits largely focused on the potential CO_2 emission reductions when RETs are used for electricity generation instead of fossil fuels.

In reviewing the possible barriers to renewable energy implementation, many of the barriers are related to outdated mind-sets, short term thinking and high capital costs. A major problem in the South African context is the complete lack of political will. It was also mentioned that these barriers should not be assessed alone, but should rather be considered as an interlinked system of barriers. Many of the possible barriers are applicable on a local level and can also be addressed at a local municipal level.

After evaluating econometrics, optimisation and simulation modelling methods, system dynamics modelling (a type of simulation model) was identified as a suitable and preferred modelling approach to model the multi-dimensional energy systems that are embedded within the multi-dimensional local Hessequa and national South African contexts. Thus parts of the first and second research objectives of this study have been addressed.

CHAPTER 3: INTRODUCTION TO THE HESSEQUA LOCAL MUNICIPALITY

3.1 Introduction to the Hessequa Municipality

The purpose of this chapter is to address the contextual aspects referred to in the first research sub-question and the first research objective. In the following paragraphs some relevant aspects of the multi-dimensional and complex domain of the Hessequa Municipality are reviewed. This chapter contextualises the research project as a single-case case study of the electric energy industry of the Hessequa Municipality as the unit of analysis.

The Hessequa Local Municipality is located within the borders of the Eden District Municipality in the Western Cape Province. The following towns/settlements fall within its borders: Heidelberg, Slangrivier, Garcia, Riversdale, Albertinia, Stilbaai, Melkhoutfontein, Gouritsmond, Jongensfontein, Witsand and Vermaaklikheid. Stilbaai and Riversdale are the two largest towns in terms of economic contribution and population. The Hessequa Municipality covers an area of approximately 5 730 km^2. Hessequa's location is presented in Figure 2.

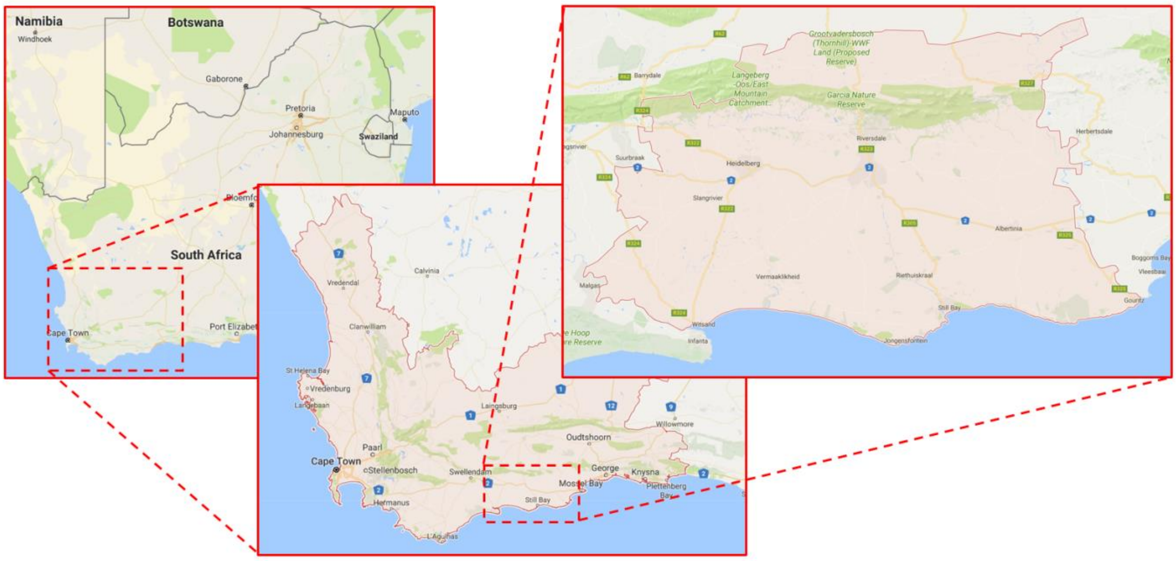

Figure 2: Location of the Hessequa municipal area

The population of 52 642 in 2011 had an average annual growth rate of 1.8% for the period 2001 to 2011 (Hessequa Municipality, 2014). About 22% of Hessequa's population live on farms and the remaining 78% live in urban areas. Between 2001 and 2011 the unemployment rate remained relatively stable at 14% (14.0% in 2001 and 14.1% in 2011) (StatsSA, 2011).

The population of 52 642 in 2011 consisted of 15 873 households (3.3 residents per household). Formal housing is available to 94.2% of residents and 4.6% of the population have access to informal housing (StatsSA, 2011). As far as ethnicity is concerned, the majority of the population (68.5%) describe themselves as Coloured, Whites contributed 23.2% and 7.4% identified themselves as Black African (StatsSA, 2011).

Hessequa Municipality stated that its vision is to create sustainable conditions for Hessequa through stabilising the pillars on which its existence depends, namely: the people, the economy and the environment.

The Constitution of South Africa listed five objectives for municipalities to achieve/deliver to the communities they serve. As a way to measure these objectives, the municipality selected six key performance areas (KPAs) (Hessequa Municipality, 2014: 6):

- “Effective communication and participation.
- Limit the impact of our presence on the natural environment to establish a heritage of preservation.
- Maintenance and development of all infrastructure and services.
- Development initiatives to enhance the safety and well-being of residents.
- Stimulate economic growth for the benefit of all communities.
- To be an accountable local authority with a fit for purpose workforce and transparent financial practices”.

These KPAs are summarised as effective communication, preservation of heritage, infrastructure and services, safe and healthy communities, economic growth, and accountable and transparent government.

The Integrated Development Plan (IDP) of the Hessequa Municipality stated that an enabling environment is required to attract new investments into the area (Hessequa Municipality, 2017). Such an environment should stimulate local economic activity, which will lead to improved businesses, job creation and aid in poverty alleviation. It also stated that retaining and expanding the existing business in the area is just as important. To help achieve this, the economic infrastructure (transport, road maintenance and building, water supply, sanitation, electricity transmission, pump stations and pipe networks) must be in place. The IDP highlights the need to identify areas of potential growth so that the appropriate infrastructure and services can be provided (Hessequa Municipality, 2014). Figures 3 and 4 illustrate the share of each major economic sector's contribution to Hessequa's economy. The biggest economic contribution changes in the 10 year period between 2002 and 2012 were in the agricultural (30.2% to 14.3%), trade (15.2% to 20.3%) and construction sectors (6.8% to 15.6%).

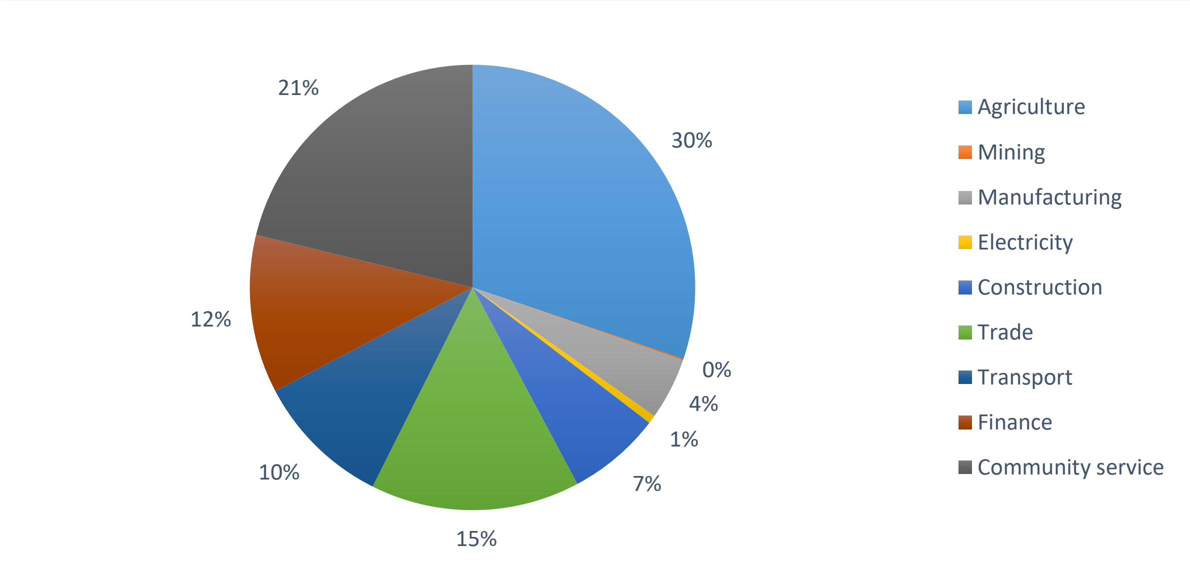

Figure 3: Sectors share of regional trade for 2002. Source: Hessequa Munuicipality (2013)

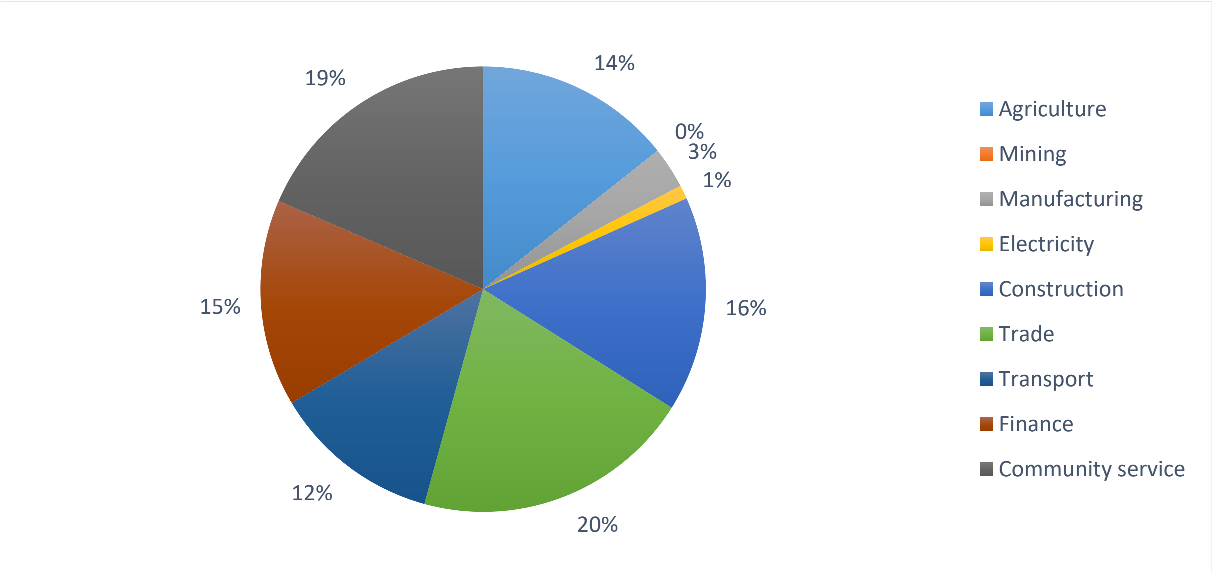

Figure 4: Sector share of regional trade in 2012. Source: Hessequa Munuicipality (2013)

As stated in section 1.3, municipalities face the risk of decreased service delivery if their income streams are compromised. Hessequa Municipality's primary sources of revenue include grants and subsidies (18.65%), property rates (17.99%), refuse removal (2.66%), electricity sales (29.73%), water sales (6.76%), sewage and sanitation (3.87%). Other income accounts for 20.33% (Grant, 2015).

3.2 The State of Renewable Energy in Hessequa

Since 2011 the Hessequa Municipality has competed in the Greenest Municipality competition and was the winner of the “Sustainable Energy” category in both 2011 and 2012. The municipality also won awards in the competitions for “Biodiversity and Coastal Management” in 2013 and 2014 (Hessequa Municipality, 2014).

Various RE studies have been conducted in the municipal area and renewable energy projects as well as energy efficiency projects have been implemented. The projects include the following:

Riversdale solar PV water purification pilot project: This pilot project hosts a 33 kW solar PV installation, which powers a water treatment plant in Riversdale. The plant began operations in November 2011 and is used to evaluate potential RE partnerships between the private sector and municipalities (Western Cape Department of Environmental Affairs and Development Planning, 2015).

Unlocking the Solar Rooftop PV Market in South Africa: A geographic information system (GIS) was used to estimate the potential size and distribution of PV installations for rooftops, specifically for Riversdale. The study identified 3638 municipal erven that were then evaluated. Criteria used to determine the suitability of a rooftop PV installation included: roof orientation and minimum installation size (1 kWp). Based on some simplifications the maximum potential for rooftop PV in Riversdale was approximately 9.85 MW with 13.7 GWh of power generated annually (Reinecke, Leonard, Kritzinger, Bekker, Van Niekerk & Thilo, 2013).

Feasibility study on the viability of charcoal and biochar production from alien vegetation in the Eden Municipality (Basson, Patel, Cohen & Rawoot, 2013)**:** Since the Eden District Municipality includes Hessequa this charcoal/biochar study is included here. The study focuses on investigating the potential benefits and negative impacts of charcoal production from invasive alien plants (IAPs). The sustainability of feedstock material, opportunities for job creation and the possible scale of operations were also investigated. The report however states that there is not enough data available in the public domain to estimate the scale of current activities or the availability of vegetation in the region. Considerations that hamper the development of biochar and charcoal projects are also discussed in the report. Some of these include a lack of policy on ownership of biomass, expensive application processes for environmental impact assessments (EIA) and atmospheric emission licenses (AEL) (in terms of both time and money), as well as a lack of funding for alien clearing projects and production operations. The report also indicates that information regarding the plant species and their distribution needs to be collected and that local government's support, engagement and co-ordination needs to improve for biomass projects to be successful.

Hessequa Energy Summit 2015: The Hessequa Energy Summit held on 23 and 24 July 2015 focused on ways to reduce the municipality's dependency on Eskom generated electricity. Generating electricity from renewable sources was one solution. When called to a vote, 64 people attending the Energy Summit voted in favour of Hessequa generating its own power versus 36 people that voted against it. Various challenges were identified with regards to providing a reliable, affordable and sustainable electricity supply. They include the need for new financing models for service provision, private and public partnerships (PPPs) need to be established to aid renewable electricity generation and an optimal energy mix for Hessequa has to be determined.

Adding renewable energy generation to Hessequa will have wider impacts than increasing energy security. RE projects may have various socio-economic benefits, such as growing a green technology industry which will create jobs and stimulate the local economy (Kruyshaar, 2015). Prof. Wikus van Niekerk from the Centre for Renewable and Sustainable Energy Studies at the University of Stellenbosch commented that solar and wind power are the best suited for local power generation. Waste-water treatment plants also have some potential. The local Korentepoort dam might be suitable for small hydropower or limited energy storage, but further studies are required to determine if these options would be cost effective.

It is clear from the highlighted projects and studies that Hessequa Municipality is welcoming the idea of renewable electricity generation and renewable energy in general. Other studies or projects regarding renewable energy generation have also been proposed in the past, but very little is evident from an implementation point of view.

3.3 Electricity demand in Hessequa

The Hessequa Municipality is the electricity service provider for all of the towns (urban areas) and rural areas within its borders, except Slangrivier, which is serviced directly by Eskom. Hessequa's electricity demand for the period 2003 – 2015 is presented in Table 7 and Figure 5. A breakdown of the individual towns was included in Appendix F. It is also interesting to note the apparent close relationship between annual GDPR growth and the change in the municipal area's electricity demand

(Figure 6). Demand peaked in 2009, decreased slightly in 2010 and has remained relatively stagnant since then (Figure 5).

Table 7: Hessequa electricity demand history. Source: Lesch (2017b)

Year	Total electricity demand	Change	Year	Total electricity demand	Change
	kWh	%		kWh	%
2003	69 930 765		**2010**	85 915 504	-1.74%
2004	73 029 483	4.39%	**2011**	86 114 688	0.23%
2005	77 513 631	5.80%	**2012**	85 591 309	-0.77%
2006	80 402 196	4.10%	**2013**	85 485 928	0.04%
2007	84 574 755	5.19%	**2014**	85 923 489	0.03%
2008	86 151 399	1.86%	**2015**	85 661 528	0.18%
2009	87 436 545	1.49%			

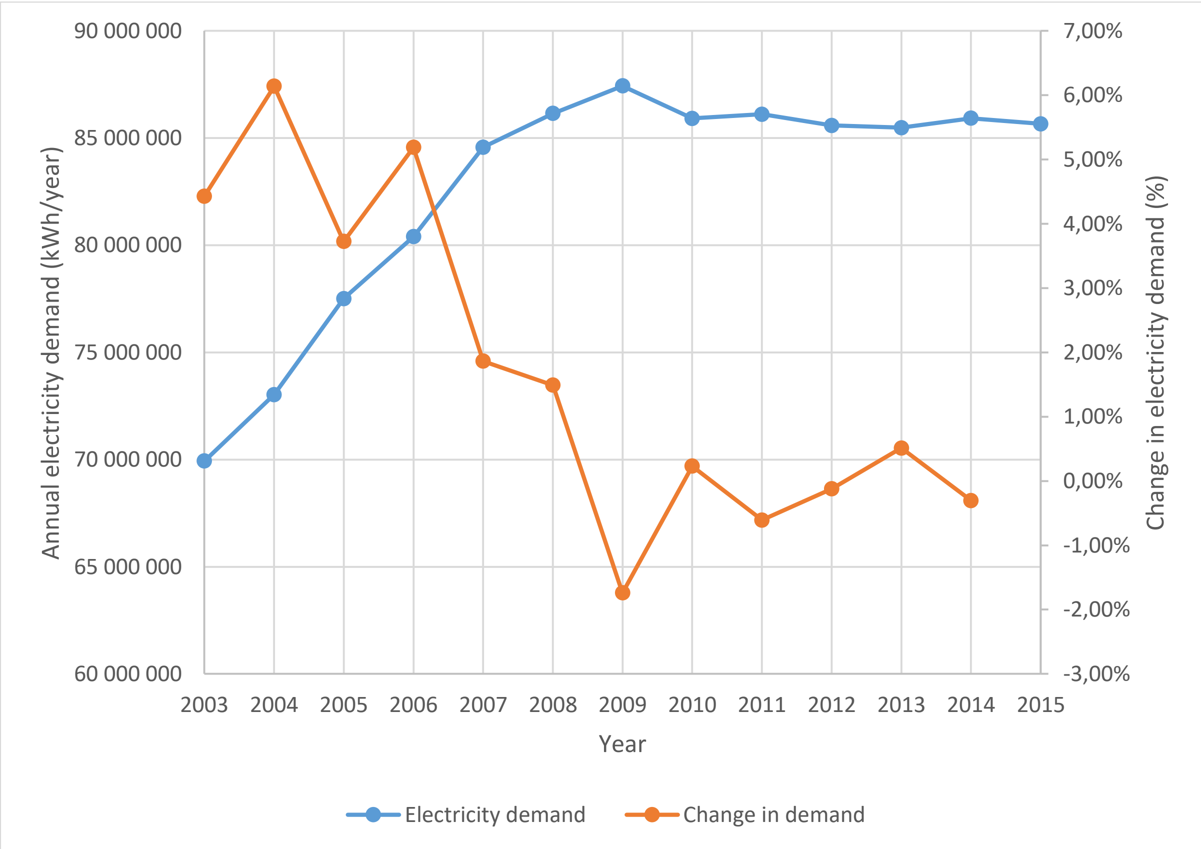

Figure 5: Hessequa's total electricity demand for the period 2003 – 2015. Source: Lesch (2017b)

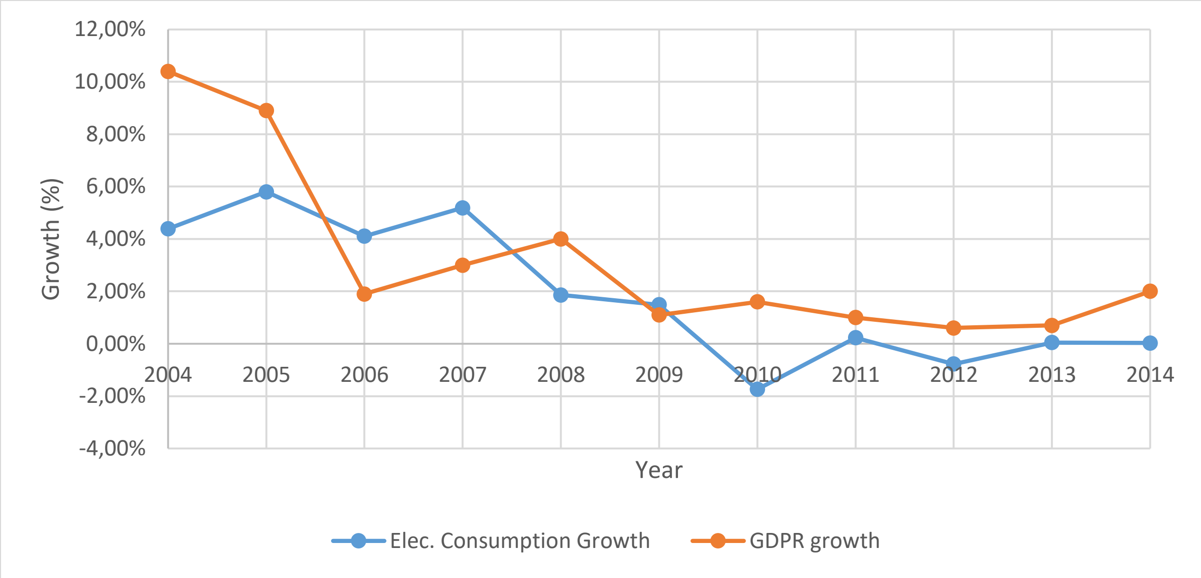

Figure 6: Hessequa's GDRP vs. electricity demand. Source: Lesch (2017b)

For most of South Africa a higher electricity demand would be expected during the winter months due to heating requirements. This is not the case in Hessequa's coastal towns. Many of these towns are popular summer holiday destinations. Due to the influx of people, electricity demand is significantly higher during the holiday season (mainly in December) than the rest of the year. Stilbaai was used as an example in Figure 7.

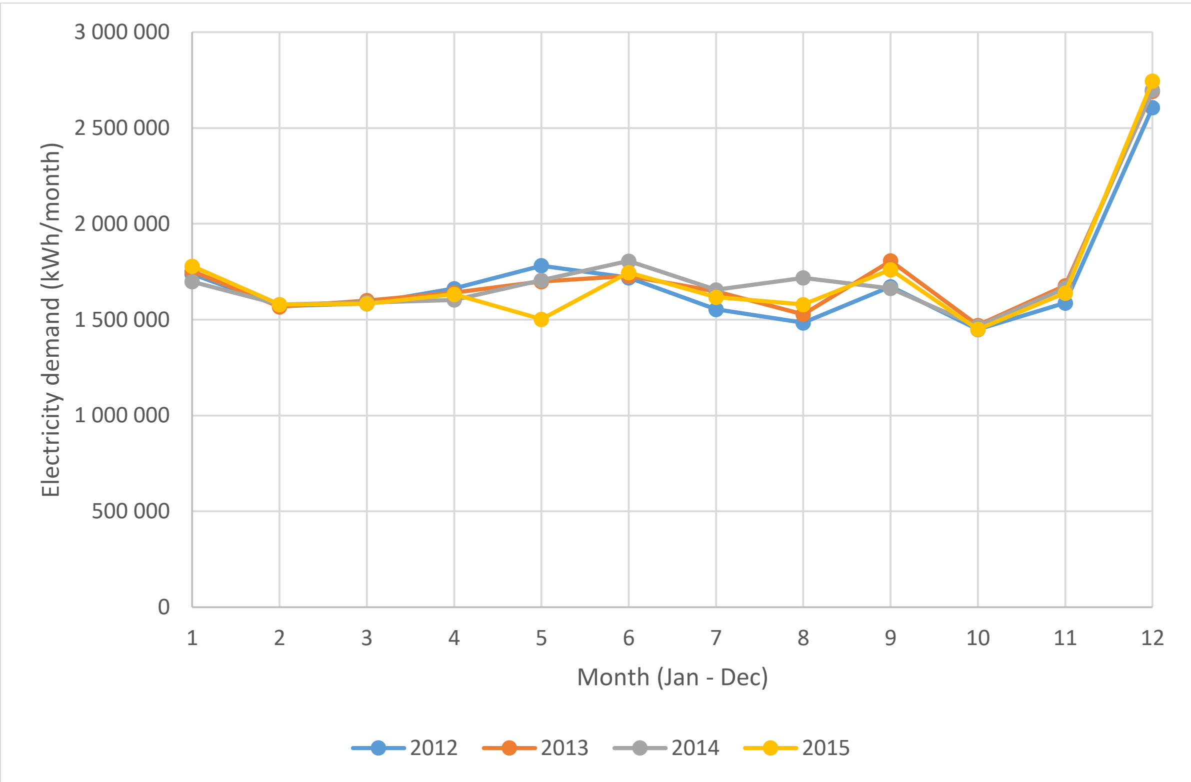

Figure 7: Stilbaai's monthly electricity demand. Source: Lesch (2017b)

3.4 The Hessequa Municipal Context in Summary

This chapter introduced the Hessequa Local Municipality as the setting for this single-case case study. A brief overview of Hessequa's socio-economic conditions were presented as well as local government's interest in creating a green environment and developing renewable energy. Most importantly, the municipal area's electricity demand behaviour was presented. In this way this chapter sketches the context within which the renewable energy solutions have to be devised as referred to in the first research sub-question and the first research objective.

The following chapter will focus on the development of a system dynamics model that can be used to help Hessequa estimate its future electricity demand, plan RET interventions, formulate policies and explore the impact of these interventions on the environment and socio-economic conditions.

CHAPTER 4: HESSEQUA RENEWABLE ENERGY MODEL DEVELOPMENT

The main objective of this chapter is to address the second research sub-question and the second research objective. This is to devise a quantitative, dynamic model that reflects the contextual realities of the Hessequa case and that can be used to find an appropriate renewable energy mix in terms of socio-economic and environmental objectives to be met simultaneously towards the year 2040.

The main focus of the Hessequa renewable energy model (HessREM) are the Hessequa Municipality's renewable electricity futures and the different possible scenarios for such futures. The processes is initiated by creating a qualitative model called a causal loop diagram (CLD). This process requires the identification of causal relationships and feedback loops in the system. Once the CLD is completed, a quantitative model can be developed (also called a stock-and-flow model). This chapter will focus on the development of the qualitative CLD and the subsequent quantitative dynamic model.

4.1 HessREM Causal Loop Diagram

Population growth and electricity demand loops (R1, B1 and B2)

A main driver of rising electricity demand is a growing population, especially in Hessequa according to a technical official (Justin Lesch) working for Hessequa Municipality (Lesch, 2017b). The reinforcing loop (R1) and balancing loop (B1) respectively indicate the population increase through births and decreasing through deaths (see Figure 8). Net migration will also have an impact on the growth of a population. Balancing loop B2 in Figure 8 describes the effects that GDP per capita have on fertility rate. Generally, greater economic and social development leads to a declining fertility rate, as seen in most developed countries across the world. Recent studies prefer to use the Human Development Index (HDI) that is a far more encompassing indicator of human well-being and development than GDP per capita. Myrskylä, Kohler and Billari (2009) found that fertility rate declined with an increase in HDI, but the trend was reversed when HDI reached a high enough level.

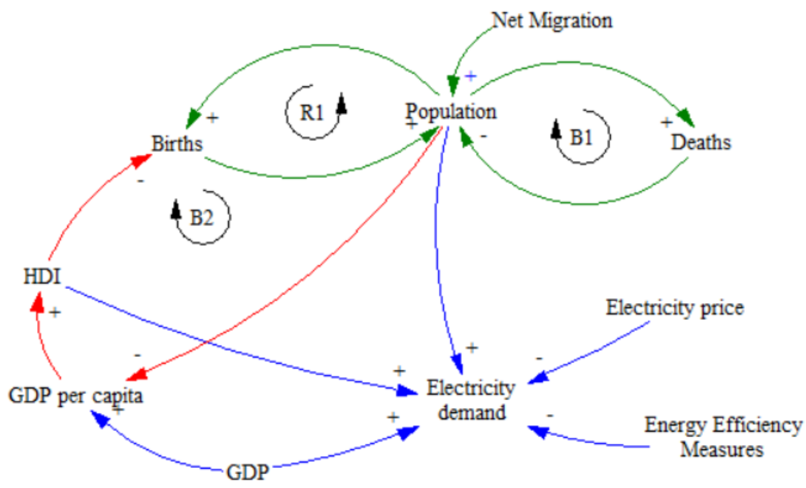

Figure 8: Population growth and electricity demand CLD

A report prepared by Frontier Economics (2007) briefly reviews models that investigated the relationship between energy consumption and wealth. The report found that energy consumption increases as wealth increases. This effect is illustrated in Figure 8 were an increase in HDI causes an increase in electricity demand.

As electricity prices increase, various efforts will focus on wasting less electricity and to make activities that consume electricity more energy efficient. This will in turn reduce electricity demand, as indicated by the causal relationship between electricity price and electricity demand in Figure 8.

Renewable electricity capacity loops (B3, B4, B5 and B6)

Modelling the Hessequa Municipality's electricity system requires it to be considered as a system defined independent from the national electricity grid, to some extent. This is technically incorrect since South Africa's grid allows for electricity generated in almost any part of the country to be used in any other part of the country. For the purpose of this model it will be assumed that the electricity demand in Hessequa that is not supplied by locally generated renewable electricity, will be supplied by Eskom and the national electricity grid.

To measure progress towards greener, renewable energy futures, the Hessequa Municipality will require a type of renewable energy goal. The renewable electricity goal (or rather goal gap) will be used to gauge the need for investment into RET generating capacity. The 'goal gap' is defined here as the difference between the renewable electricity target of 33.3% of total local demand, and the actual RET generation. The investment capital will then be used to expand the RET generating capacity. The process of creating a new RE facility requires a couple of years to complete due to the long planning process, environmental impact assessments, construction and commissioning time. This time delay between the decision to invest and the actual commissioning and operation of RE generating capacity is incorporated into the balancing loop B3 in Figure 9 (the parallel lines in the link between RE investment and RE generating capacity denotes a delay). Increased RE capacity would enable Hessequa to generate more renewable electricity and in doing so, reduce the goal gap indicated in Feedback loop B3.

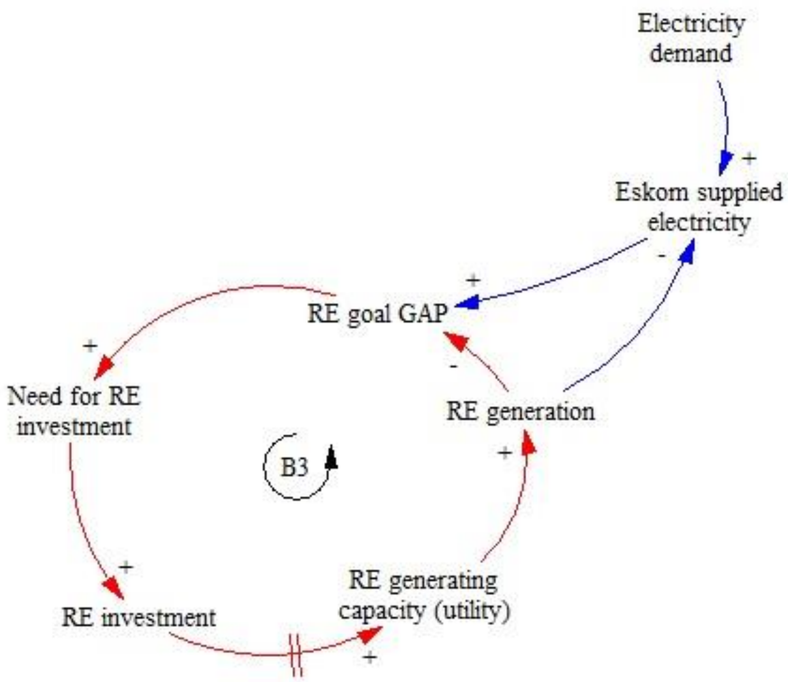

Figure 8: Renewable electricity capacity expansion CLD

Most technologies have a limited life span. Over time facilities depreciate, become more expensive to maintain or the technology becomes outdated. Eventually these facilities are decommissioned or retired at the end of their lifespan. This process is demonstrated in the balancing loop B4 in Figure 10 and the delay sign is once again used to indicate the time between commissioning of new RET generation capacity and retirement of that capacity. The actual time delay will be dependent on the average lifespan of the different technologies.

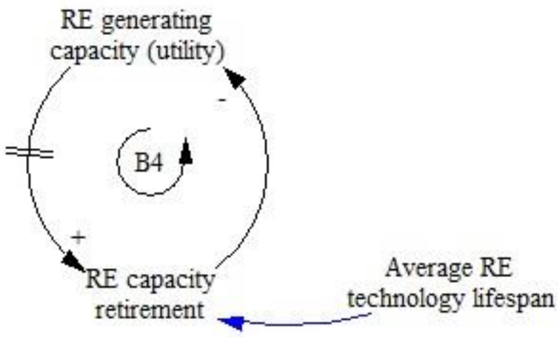

Figure 9: Renewable electricity generation capacity decommissioning CLD

Aside from utility scale renewable energy installations, small scale embedded generation capacity like rooftop solar PV panels and small scale wind turbines can also contribute towards renewable energy generation in Hessequa. One of the major factors driving households towards small scale renewable energy solutions is Eskom's rising electricity prices and the falling costs of small scale electricity generation systems (Figure 11).

The towns in Hessequa are serviced by medium voltage feeders with a peak line capacity. Eskom has connection criteria stating that embedded generation may not exceed 15% of the peak line capacity. However, this applies to generation capacity that is connected to the grid, but not to off grid capacity. Therefore, should grid-connected embedded generation like rooftop PV installations approach this limiting criteria, policies or bylaws will have to be put in place to limit further installations. This balancing feedback (B5) loop is presented in Figure 11. It is however unlikely that this maximum capacity will be reached in the foreseeable future since small scale generation is not quite affordable for everyone yet. It is expected that only higher income households will consider installing small scale generation to take their homes off-grid. As more and more of these high income households install rooftop PV systems (for argument's sake), the market of those who can afford it will become more and more saturate leading to a decline in new small scale RE installations, as demonstrated in the balancing loop B6 in Figure 11. These systems degrade over time like any technology, but given the 25 year commercial warranties of PV panels and degradation rates below 1%/year (Jordan & Kurtz, 2013), retirement of embedded solar PV systems were not included in the causal loop diagram.

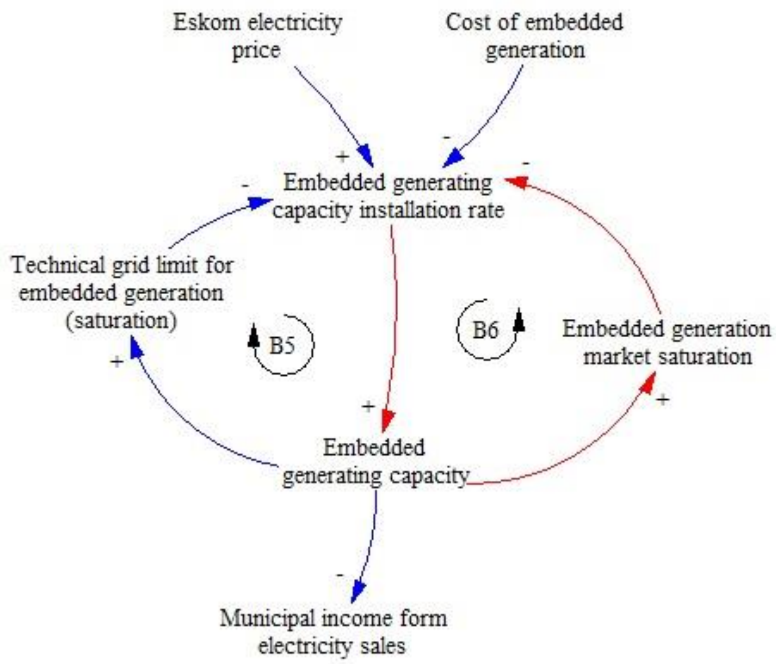

Figure 10: Embedded small scale RE generation CLD

Aggregate causal loop diagram

Figure 12 presents an aggregated causal loop diagram that was used to develop the stock-and-flow model which is discussed later in this chapter. Figure 12 also illustrates the fact that an increase in RET generation capacity will lead to reduced GHG emissions. Another aspect of the system highlighted in Figure 12 is RET's impact on unemployment. As Hessequa's RET capacity grows, so does the number of job opportunities.

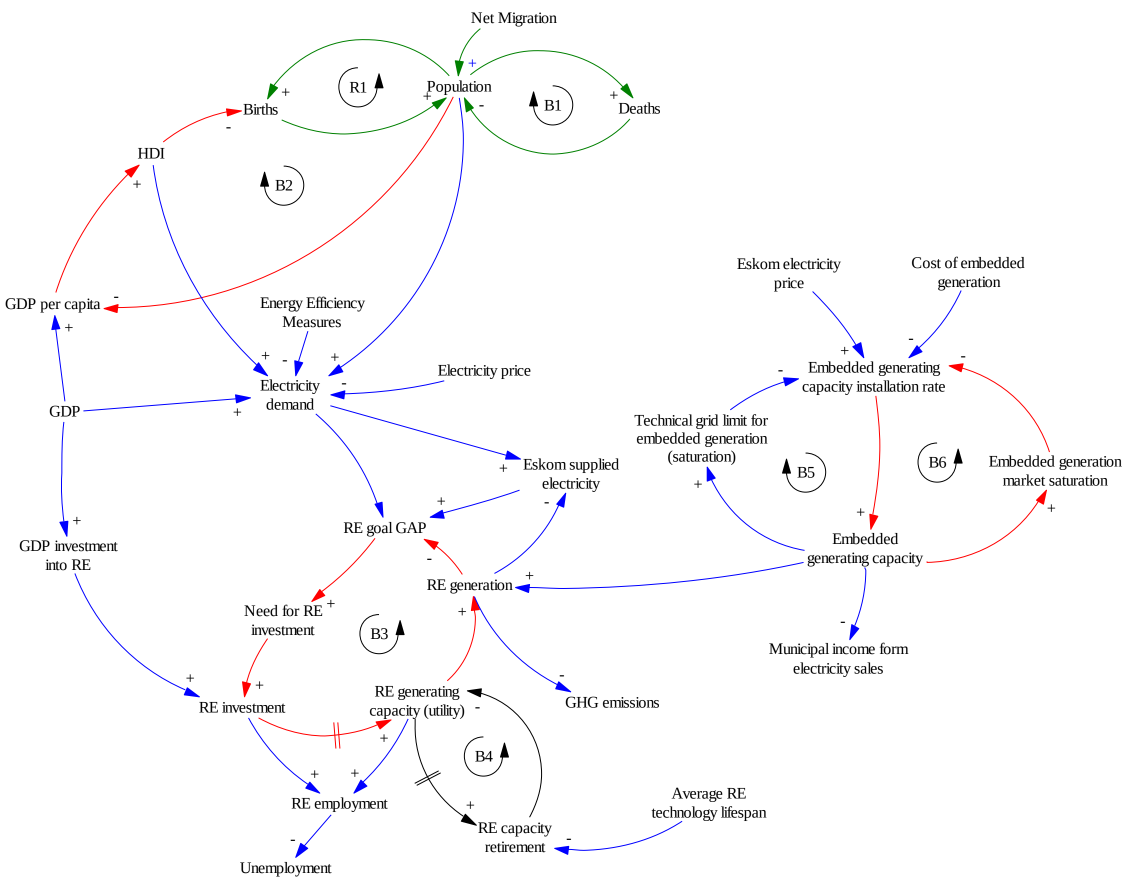

Figure 11: Integrated renewable electricity CLD for the Hessequa Municipality

4.2 HessREM Stock-and-Flow Model Development

The following section will focus on the stock-and-flow model developed from the causal loop diagrams that are presented in section 4.1. Each of the individual sub-models deal with a different aspect of the system.

4.2.1 Utility scale power sub-models

Technologies considered for utility scale power generation in the Hessequa Municipality include wind power, solar PV, biomass power (by gasification) and hydropower as pumped storage. Stock-and-flow diagrams for the selected technologies were all modelled based on the structures presented in the work of Ford (2001), Qudrat-Ullah (2013), UNEP (2013) and Oosthuizen (2016). The basic model structure for all technology options are the same and is illustrated in Figure 13. Initially, the renewable energy generation goal gap triggers the need for RET investment, thus initiating a new RET project.

The planning and construction phases of power plants are prone to many delays such as environmental impact assessments, approval from the proper authorities and other unforeseen events. Once planning and construction of the new generation capacity is complete it forms part of the operational generation capacity. During their operational lifetime plants tend to degrade, which leads to reduced productivity and thus decreased electricity generation. As the plants degrade and efficiencies are reduced, the operational capacity is depreciated as illustrated in Figure 13.

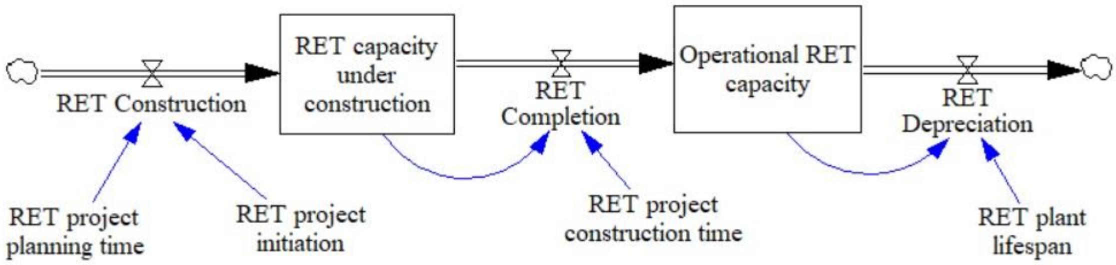

Figure 12: Basic stock-and-flow diagram structure for RET capacity

When funds become available for RET investment ($Investment_{RET,i}$), a specific portion of the funds can be allocated to a specific RET like wind or solar power. The annual RET capacity that enters the construction phase of a project ($CGC_{RET,i}$) is determined by dividing the available investment for that specific RET by its capital cost ($CC_{RET,i}$) (Equation 1). Generation capacity under construction ($GCC_{RET,i}$) was modelled as a stock. The stock is emptied as construction is completed ($ComGC_{RET,i}$), as illustrated in Equation 2.

Equation 1

$$CGC_{RET,i}\,(t) = \frac{Investment_{RET,i}(t)}{CC_{RET,i}\,(t)}$$

Equation 2

$$GCC_{RET,i}(t) = \int_{t_0}^{t}\left[CGC_{RET,i}(s) - ComGC_{RET,i}(s)\right]ds + GCC_{RET,i}(t_0)$$

Each of the RETs have different capacity factors. The annual electricity generated by each technology is calculated by multiplying the installed generation capacity with a capacity factor ($F_{C,i}$) and an energy conversion factor (F_{EC}) which is basically the total number of hours in a year (Equation 3). This method is only used when more accurate data is not available to estimate potential electricity generation.

Equation 3:

$$EG_{RET,i}(t) = GC_{RET,i}(t) \times F_{c,i} \times F_{EC}$$

When more accurate estimates can be made for electricity generation (wind and solar PV power), a capacity factor equivalent ($F_{CE,i}$) is calculated for the purposes of comparing between technology options. Capacity factors (or capacity factor equivalents) are also used to calculate a capacity conversion factor ($F_{CC,i}$) for each technology. This factor is used elsewhere in the model (see section 4.2.15). The capacity factor equivalent is determined by dividing the estimated annual electricity generation from a given RET by the maximum annual electricity generated of that technology (assuming it was working at full capacity 100% of the time at 100% efficiency). Capacity conversion factors are calculated by multiplying the capacity factors (or capacity factor equivalents) with the energy conversion factor. The calculations are presented in Equations 4 - 6.

Equation 4

$$F_{CE,i} = \frac{EG_{RET,i}(t)}{Max\ Annual\ Generation_{RET,i}}$$

Equation 5

$$F_{CC,i} = F_{CE,i} \times F_{EC}$$

Equation 6

$$F_{CC,i} = F_{C,i} \times F_{EC}$$

Each sub-module for utility power generation technologies is briefly discussed in sections 4.2.2 – 4.2.5.

Appendix E contains detailed information on the renewable resources that can be used for electricity generation in the Hessequa Municipal Area (for the cases where information was available).

4.2.2 Wind power sub-model

The utility scale wind power sub-model follows the general utility scale power structure presented in section 4.2.1. The operational lifespan for a wind power plant is assumed to be 25 years (Centre for Climate and Energy Decision Making, 2015).

The wind turbine specifications of the Siemens SWT – 2.3-101 (Siemens, 2017) are used for estimating electricity generation from the operational wind power capacity. Wind resource data is gathered at 100 m above ground level (see Appendix E), but turbine hub heights are only 80 m. The wind power law (Equation 7) is thus used to determine wind speeds at 80 m. The unknown wind speed is presented by u, u_r is the reference wind speed, z is the hub height, z_r is the reference height where the wind speed is measured and α is a constant.

Equation 7

$$u = u_r \left(\frac{z}{z_r}\right)^{\alpha}$$

Equation 8 is used to calculate the available power (P_{avail}) from each wind turbine. A is the turbine sweep area, ρ is air density, v is air velocity (wind speed) and C_p is a power coefficient.

Equation 8

$$P_{avail} = \left(\frac{1}{2}\right) \rho A v^3 C_p$$

The average number of turbines available at any given time is estimated by dividing the operational wind power capacity by the nominal power capacity of a single Siemens SWT-2.3-101 turbine (Equation 9). The electricity generation from the operational capacity is then estimated by multiplying the number of turbines by the available power of each turbine (Equation 10).

Equation 9

$$Number\ of\ Turbines(t) = \frac{GC_{Wind}(t)}{2300\ kW}$$

Equation 10

$$EG_{Wind}(t) = Number\ of\ Turbines(t) \times P_{avail}$$

4.2.3 Biomass power sub-model

The biomass power sub-model also follows the utility scale power structure described in section 4.2.1. Biomass power utilises a capacity factor for estimating annual electricity generation. The fuel harvesting aspect of biomass power was described in detail in Appendix E.

4.2.4 Pumped storage power sub-model

Pumped storage also follows the utility scale power structure described in section 4.2.1. A capacity factor is again used for estimating annual electricity generation. More detailed estimates will be speculation at the time of writing since no formal studies have been conducted on the pumped storage potential of Hessequa's reservoirs.

4.2.5 Solar PV power sub-model

Solar PV (utility scale solar power) follows the utility scale power structure described in section 4.2.1 as well. The calculations used for utility Solar PV and rooftop PV electricity generation are similar. Refer to Section 4.2.6 for a description of this procedure.

4.2.6 Rooftop solar PV sub-model

Reinecke *et al.* (2013) claims that the primary driving force for potential owners to invest in embedded generation is a financial one (assuming they would save money in the long term). The market for embedded generation in this work is considered to only be the residential sector. In reality many businesses may also choose to invest in these systems. Other motivations for investing in renewable embedded generation could include, but is not limited to the following:

- Reducing dependence on Eskom (because the utility is considered to be unreliable regarding electricity supply).
- The ever increasing price of electricity generated by Eskom.
- Falling capital cost of renewable energy technologies, especially solar PV panels.
- Environmental consciousness.

In the model, the main drivers for rooftop PV installation include the rising price of grid based electricity ($II_{Electrcitiy\ Price}$), falling capital costs of rooftop PV systems ($II_{RE\ Capital\ Cost}$) and a municipal feed-in-tariff (II_{FIT}). These drivers are included as multiplier effects that follow an S-curve. As Eskom electricity becomes more expensive, incentive to invest in rooftop PV systems increase. As the capital cost of rooftop PV systems fall, the incentive to invest also increases. The feed-in-tariff incentive does not follow an S-curve. It was assumed that the municipality will pay a feed-in-tariff equal to the real cost of rooftop PV electricity. In reality the municipality might decide not to pay a feed-in-tariff. In this case, the feed-in-tariff incentive will be zero. The total Installation Incentive

(II_{Total}) is a combination of these three incentives (see Equation 11). Each incentive contributes a fraction of the total installation incentive as follows:

- II_{FIT} : 0.3
- $II_{Electricity\ Price}$: 0.3
- $II_{RE\ Capital\ Cost}$: 0.4

Equation 11

$$II_{Total}(t) = 0.4\left(II_{RE\ Capital\ Cost}(t)\right) + 0.3\left(II_{Electrcity\ Price}(t)\right) + 0.3(II_{FIT}(t))$$

In 2011, NERSA proposed standard conditions for embedded generation within municipal boundaries (NERSA, 2011). It requires local municipal authorities to compile a database of information relating to the type of technology, installed capacity, electricity generated, location, energy storage and personal details of the owners of all embedded generation smaller than 100 kW. At the time of writing, NERSA and the Department of Energy have still not finalised these conditions and reporting requirements. There was thus no concrete local level data available for installed embedded generation capacity. An initial installed generation capacity ($GC_{Rooftop\ PV}$) and a base installation rate ($IR_{Rooftop\ PV\ Base}$) had to be assumed.

As with most technologies, the efficiency of solar PV panels degrade over time. According to Van Niekerk (2013), after 25 years these panels retain approximately 80% of their rated power generation capacity. A degradation factor (F_{Deg}) of 0.8% per year is thus used to account for the loss of productivity in rooftop PV panels. Rooftop solar PV degradation ($D_{Rooftop\ PV}$) was estimated by multiplying the degradation factor with the installed rooftop solar PV capacity ($GC_{Rooftop\ PV}$) (see Equation 12). The operational rooftop solar PV capacity at any given time can be calculated using Equation 13.

Equation 12

$$D_{Rooftop\ PV}(t) = GC_{Rooftop\ PV}(t) \times F_{Deg}$$

Equation 13

$$GC_{Rooftop\ PV}(t) = \int_{t_0}^{t}\left[IR_{Rooftop\ PV}(s) - D_{Rooftop\ PV}(s)\right]ds + GC_{Rooftop\ PV}(t_0)$$

There is a technical limit to grid connected embedded generation as discussed by Reinecke *et al.* (2013). Their estimated uptake of embedded generation was however well below this technical limit for Riversdale. Since Riversdale has the strongest economy in Hessequa, it is relatively safe to assume that embedded generation uptake would be the highest there (more people are likely able to afford it). The technical limit for embedded generation are thus not be considered a limiting factor for privately owned embedded generation in this model, but it still needs to be monitored for grid safety reasons.

For the model, the specifications of a SD 210 Power solar PV panel were assumed as described on Solar Direct (2016). To determine the average power-to-surface area ratio (R_{PA}) of a single panel, the panel's power rating is divided by its surface area (154.67 W/m^2). To estimate the total rooftop area covered in PV panels, the installed rooftop solar PV capacity is divided by the panel's power-to-surface area ratio (Equation 14).

Equation 14

$$A_{Rooftop\ PV}(t) = \frac{GC_{Rooftop\ PV}(t)}{R_{PA}}$$

Equation 15 (Photovoltaic software, 2016) is then used to estimate the annual electricity generation from the installed rooftop PV capacity. Panel efficiency is presented by r, PR is the performance ratio and H is the annual solar radiation on the panel. Information regarding the annual radiation is available in Appendix E.

Equation 15

$$EG_{Rooftop\ PV}(t) = A_{Rooftop\ PV}(t) \times r \times PR \times H$$

As stated, although the capital cost of rooftop PV systems are decreasing, they are still in a high enough price range to make them unaffordable to many households. The model estimates a possible market for rooftop PV installations based average household income levels. Only those households that have an average annual income of R 614 401 or more are considered to potentially invest in a rooftop PV system. As more households install these systems the market becomes saturated and the drive for new installations decreases, forming a balancing loop. In the model it is implemented as follows:

- An average household PV system capacity ($PV\ Capacity_{Avg.Res.}$) of 5 kWp is assumed.
- The number of households above a certain income level ($Households_{HIL\ 10+}$) is estimated by utilising census data (StatsSA, 2011).

- The potential rooftop PV market ($PV\ Market_{Residential}$) is estimated by multiplying the number of qualifying households with the average size of a residential rooftop PV system (see Equation 16).

Equation 16

$$PV\ Market_{Residential}(t) = PV\ Capacity_{Avg.Res.} \times \sum_{i=HIL_{10}}^{HIL_{12}} Households_i(t)$$

- A rooftop PV market saturation ratio (SR) is then calculated by dividing the installed rooftop solar PV capacity ($GC_{Rooftop\ PV}$) by the potential rooftop PV market (Equation 17).

Equation 17

$$SR(t) = \frac{GC_{Rooftop\ PV}(t)}{PV\ Market_{Residential}(t)}$$

- An S-curve is then used to convert the saturation ratio to a saturation factor ($SF_{PV\ Market}$).

The actual installation rate for rooftop solar PV systems ($IR_{Rooftop\ PV}$) is then calculated using Equation 18.

Equation 18

$$IR_{Rooftop\ PV}(t) = \left(IR_{Rooftop\ PV\ Base}\right) \times (II_{Total}(t) - SF_{PV\ Market}(t))$$

The model provides an option to feed a portion of the rooftop PV electricity generated back into the grid. On-site supply might be higher than on-site demand during certain times of the day. The excess electricity can then be used elsewhere in the grid. Equation 19 calculates the estimated excess electricity that is fed back into the grid ($EG_{Rooftop\ PV\ Grid}$) by multiplying the rooftop PV electricity generation by a fraction ($F_{Rooftop\ PV\ Grid}$).

Equation 19

$$EG_{Rooftop\ PV\ Grid}(t) = F_{Rooftop\ PV\ Grid} \times EG_{Rooftop\ PV}(t)$$

The model assumes that rooftop PV uptake continues regardless of the municipality paying a feed-in-tariff for the electricity being fed back into the grid. As stated, under business-as-usual conditions the only incentives driving rooftop PV installation are the falling capital cost of embedded generation and the rising price of grid based electricity.

4.2.7 Electricity supply sub-model

To measure progress towards reaching Hessequa's RE goal, estimate of both electricity supply and demand are required. The electricity supply sub-model represents the total renewable electricity supply of Hessequa as well as the deficit, which was assumed to be supplied by Eskom. The sub-model also calculates the operational capacity share of each renewable electricity technology.

Utility scale generation capacity is assumed to be connected to the local electricity grid. This includes generation from pumped storage, biomass, solar PV and wind power. The model also has the option to vary the amount of rooftop PV fed into the grid. Grid connected electricity generation ($EG_{Grid\ connected}$) is calculated by summing all electricity generation (EG_{RET_i}) from RETs in Hessequa and the Eskom electricity consumed (EG_{Eskom}) (Equation 20). The share of each technology's electricity generation as a fraction of the total grid connected electricity is also calculated using Equations 21 to 23.

Equation 20

$$EG_{Grid\ connected}(t) = \sum EG_{RET,i} + EG_{Eskom}(t) + EG_{Rooftop\ PV\ Grid}(t)$$

Equation 21

$$Grid\ Share_i(t) = \frac{EG_{RET_i}(t)}{EG_{Grid\ connected}(t)} \times 100\%$$

Equation 22

$$Grid\ Share_i(t) = \frac{EG_{Eskom}(t)}{EG_{Grid\ connected}(t)} \times 100\%$$

Equation 23

$$Grid\ Share_i(t) = \frac{EG_{Rooftop\ PV\ Grid}(t)}{EG_{Grid\ connected}(t)} \times 100\%$$

The total renewable electricity generation in Hessequa (REG_{Total}) (Rooftop PV included) is calculated using Equation 24.

Equation 24

$$REG_{Total}(t) = \sum EG_{RET,i}\ (t)$$

It is assumed that Eskom supplies the balance of Hessequa's total end user electricity demand ($TEUED$) that is not supplied by RETs (see Equation 25).

Equation 25:

$$EG_{Eskom}\ (t) = TEUED(t) - REG_{Total}(t)$$

For technical and non-technical reasons, electrical losses occur during transmission and distribution of electrical energy. These losses are taken into account for renewable electricity generation. Hessequa's financial statements reports a distribution loss factor of 9.81% (Hessequa Municipality, 2016). Bhattacharyya and Timilsina (2010) states that the loss factor can be reduced when electricity is used closer to where it is generated. Hessequa's electricity generation will most likely be distributed and thus the loss factor (F_{Dist}) will probably be smaller than the reported 9.81% (it was assumed to be 9.81% in the model). Electricity lost during distribution (EG_{Lost}) and the net consumable renewable electricity ($EG_{Net\ Consumable\ RE}$) can then be calculated from Equation 26 and 27 respectively.

Equation 26

$$EG_{Lost}(t) = REG_{Total}(t) \times F_{Dist}$$

Equation 27

$$EG_{Net\ Consumable\ RE}(t) = REG_{Total}(t) - EG_{Lost}(t)$$

The share of Hessequa's electricity demand that is supplied by renewable electricity ($RESS$) is calculated in Equation 28 and can be used as an indicator to measure progress towards becoming electricity independent.

Equation 28:

$$RESS(t) = \frac{EG_{Net\ Consumable\ RE}(t)}{TEUED(t)} \times 100\%$$

A goal-gap is used in the model instead of a supply-demand gap, due to the fact that no real supply-demand gap exists at this system level. Firstly a renewable energy generation goal ($REGG$) is set in terms of the share of Hessequa's total end user electricity demand that is met with renewable electricity. This goal is defined as part of a policy decision at the start of the modelling period. The renewable energy generation required to meet the goal ($REGRG$) is determined by multiplying Hessequa's total end user electricity demand by the renewable energy generation goal. By subtracting the renewable energy generation required to meet the goal from total end user electricity demand, the renewable energy generation goal gap ($REGGG$) can be determined. Equations 29 and 30 show these calculations. The MAX function used in Equation 30 prevents the REGGG from containing a negative value. A negative REGGG value will cause a negative demand in investment in RETs, which does not make sense in reality (see section 4.2.15).

Equation 29

$$REGRG(t) = REGG \times TEUED(t)$$

Equation 30

$$REGGG(t) = MAX[REGRG(t) - EG_{Net\ Consumable\ RE}(t), 0]$$

The renewable energy goal progress ($REGP$) is also calculated in the model using Equation 31. It is expressed as a fraction and indicates how close Hessequa is to achieving its renewable energy goal.

Equation 31

$$REGP(t) = \frac{EG_{Net\ Consumable\ RE}(t)}{REGG \times TEUED(t)}$$

4.2.8 Electricity cost sub-model

Different approaches are followed for estimating the future cost of Eskom electricity and renewable electricity. To negate the impact of inflation, the model estimated both the real and relative real cost of Eskom electricity. Due to uncertainty in South Africa's present and future economic conditions, it is difficult to estimate future values of the country's inflation. For the period 2006 – 2016, the annual average inflation fluctuated drastically. This was however under global economic recession conditions. For the period 2012 – 2016, inflation was relatively stable, varying between an annual average of 4.51% and 6.59% (Inflation.eu, 2017). As part of its monetary policy, the South African Reserve Bank aims to keep inflation between 3% and 6% (South African Reserve Bank, 2017). Thus, an average annual inflation rate of 6.00% is assumed when calculating Eskom's real future electricity tariffs. Furthermore, historic tariff data for Eskom's electricity and renewable electricity tariffs are obtained from Eskom's website (Eskom, 2016b) and documents discussing the REIPPP programme (South Africa - Department of Energy, 2015; GreenCape, 2016). An average annual tariff hike of 8% is assumed for Eskom electricity. This is not considered to be unreasonable as Eskom's electricity prices have increased approximately 500% since 2007 when the state owned enterprise started its tariff hikes.

Eskom plans to increase tariffs an additional 20% in 2018 (Groenewald, 2017). It is also assumed that any Eskom electricity tariff increases would be relatively uniform across all consumer sectors. Because of this assumption, the model can utilise an average Eskom electricity cost instead of considering different electricity costs for different sectors. Equations 32 and 33 are used to calculate the real (REC_{Eskom}) and relative real Eskom electricity costs ($RREC_{Eskom}$). The real electricity costs are calculated using 2017 as the base year. Average annual tariff hikes are indicated by $i_{Tariff\ Hike}$, and $i_{inflation}$ represents the annual inflation rate.

Equation 32

$$REC_{Eskom,Year\ X}(t) = REC_{Eskom,Base\ Year}\left(\frac{1+i_{Tariff\ Hike}}{1+i_{inflation}}\right)^{(Year\ X - Base\ Year\ )}$$

Equation 33

$$RREC_{Eskom,Year\ X}(t) = \left(\frac{REC_{Eskom,Year\ X}}{REC_{Eskom,Base\ Year}}\right)$$

Learning curve effects are used to estimate the future cost of electricity generated by different RETs. The learning curves are based on the estimated future capital cost decreases of each RET. Initial electricity costs are estimated from REIPPPP tariffs (Initial rooftop PV electricity costs are assumed to be equal to that of utility solar PV). The real future RE electricity costs ($REC_{RET,i}$) are calculated by multiplying the initial RE electricity cost with a learning effect (Equation 34). The learning curves are included in Appendix D.

Equation 34

$$REC_{RET,i}(t) = REC_{RET,initial} \times Learning\ Effect_{RET,i}(t)$$

An additional effect is included for rooftop PV electricity. When the local government decides to pay a feed-in-tariff for electricity fed back into the grid, they essentially buy electricity from the owners of embedded generation systems. When they pay no feed-in-tariff the electricity is still fed back into the grid, but it can be considered as free (from the local government's point of view). This is included in the model by using a feed-in-tariff factor (F_{FIT}). The feed-in-factor can be varied depending on how much the municipality is willing to pay for the embedded generation electricity being fed into the grid (Equation 35).

Equation 35

$$REC_{Rooftop\ PV}(t) = RET_{Rooftop\ PV,initial} \times Learning\ Effect_{Rooftop\ PV}(t) \times F_{FIT}$$

A real Hessequa electricity cost is then calculated. It is based on the cost of electricity from Eskom as well as each RET, and their respective contributions to grid based electricity (Equation 36). The same approach is followed when determining a relative real electricity cost (Equation 37).

Equation 36

$$REC_{Hessequa}(t) = \sum \left(Grid\ Share_i(t) \times REC_{RET_i,Year\ X}(t) \right)$$

Equation 37

$$RREC_{Hessequa}(t) = \sum \left(Grid\ Share_i(t) \times RREC_{RET_i,Year\ X}(t) \right)$$

Relative real electricity costs are considered a more robust measure of electricity costs than real electricity costs in the long term. These costs are also assumed to be the price that local government pays for electricity. After local government adds its mark-up for resale of electricity, the real ($RETariff_{Hessequa}$) and relative real Hessequa electricity tariffs ($RRETariff_{Hessequa}$) are calculated. This is the cost of electricity to the consumer that purchases electricity from local government. That part of the model is discussed in section 4.2.16 which provides more details regarding the impacts on local government.

4.2.9 Electricity demand sub-model

Kebede, Kagochi and Jolly (2010) states that economic growth is directly related technological development and energy use. It is thus important to investigate the factors that impact energy demand. Estimating future electricity demand is an important aspect of any energy related planning activity. Different sectors of the economy grow at different rates. Their electricity demands are therefore also likely to grow at different rates. The sectors considered in this model include residential, commercial, industrial, agricultural and also the local government sector. When a reasonable estimate of future electricity demand can be made, planning can commence for the appropriate new generation capacity that can meet the demand (or goal, in the case of smaller areas such as Hessequa).

According to Hessequa's IDP (Hessequa Munuicipality, 2013) the major economic sectors in the municipality (in terms of their contribution to gross economic value added in 2012) include agriculture, mining, manufacturing, electricity, construction, trade, transport, finance and community services. To incorporate all these factors separately into the model would be unpractical due to the limited data availability on local level. Instead, these sectors are grouped together as "Business".

It is important to take into account the demand elasticity of electricity when estimating future electricity demand. Price elasticity of demand is defined as the percentage change in demand divided by the percentage change in price (Bernstein & Griffin, 2006) (see Equation 38).

Equation 38:

$$Price\ Elasticity\ of\ Demand = \frac{\%\ \Delta\ quantity\ demanded}{\%\Delta\ price}$$

The demand of a product is said to be elastic when a small change in price has a big impact on the quantity demanded. Conversely, the demand for a product is said to be inelastic when a large change in price only has a small impact on the quantity demanded. Where price elasticity is concerned, elasticity is usually in the negative range, indicating that an increase in price causes a decrease in demand and vice versa. Elasticity can be categorised into types, namely elastic and inelastic. Inelastic elasticity values range from 0 to 1 and elastic values for elasticity are greater than 1. When elasticity is exactly equal to 1, it is referred to as being unit elastic and indicates that any change in price causes a proportionate change in demand (Bernstein & Griffin, 2006).

Elasticity of demand can depend on factors other than price. In the case of electricity the change in demand are sensitive to changes in the different drivers of electricity demand. These drivers also vary between the sectors under consideration. To account for the impact of different drivers having different impacts on the municipal area's electricity demand, consumers are separated into 3 sectors. According to Oosthuizen (2016), separating the consumer sectors provides a more accurate and detailed method of predicting future electricity demand than an aggregate approach. It also provides better insight to the evolution of electricity demand over time. Deloitte (2012) claims that economic growth, especially for South Africa, and prices are key long-term drivers for electricity demand. The consumer sectors and the drivers that impact each sector are included in Table 8.

Table 8: Electricity demand drivers for consumer sectors

Sector	Electricity demand drivers
Residential	Population, GDPR per capita, Electricity price
Business	GDPR, Electricity price
Local Government	Population, Electricity price

The end user electricity demand ($EUED$) of all three sectors mentioned in Table 8, are modelled as stocks. The initial electricity demand (IED_i) of each sector is used to initialise the stocks. To calculate the current year's electricity demand for a given sector ($New\ EUED_i$), the initial end user electricity demand (IED_i) is multiplied by the demand drivers for that sector (Equation 39 to 41). The effect of regional gross domestic product and the effect of electricity price is indicted by $EGDPR$ and EPE respectively. The effects of regional gross domestic product per capita and population are respectively indicated by $EGPC$ and EP.

Equation 39:

$$New\ EUED_{Business}(t) = IED_{Business}\ \times EGDPR(t) \times\ EPE_{Business}(t)$$

Equation 40:

$$New\ EUED_{Residential}(t) = IED_{Residential}\ \times EGPC(t) \times\ EPE_{Residential}(t) \times EP(t)$$

Equation 41:

$$New\ EUED_{Local\ Government}(t) = IED_{Local\ Government}\ \times EPE_{Local\ Government}(t) \times EP(t)$$

To determine how much end user electricity demand changes each year, the new end user electricity demand ($New\ EUED_i$) is subtracted from the end user electricity demand ($EUED_i$) value still in the stock from the previous simulation iteration (Equation 42). Each end user of electricity stock is calculated for the current simulation iteration using Equation 43.

Equation 42

$$EUED\ Growth_i\ (t) = New\ EUED_i(t) - EUED_i(t)$$

Equation 43

$$EUED_i(t) =\ \int_{t_0}^{t} EUED\ Growth_i\ (s)\ ds + EUED_i(t_0)$$

To calculate the total electricity demand for a point in time, the sectoral electricity demands are summed together as illustrated in Equation 44.

Equation 44:

$$TEUED(t) = EUED_{Residential}(t) + EUED_{Local\ Government}(t) + EUED_{Business}(t)$$

On a local level, gathering data on the electricity demand of various sectors is challenging. According to a report by the Western Cape Government (Western Cape Government, 2013c) Eskom does not collect data past municipal boundaries, this is the responsibility of local government. Hessequa's information systems do not allow consumers to be readily grouped into different sectors. Client confidentiality also becomes an obstacle when gathering data at the local municipal level. Assumptions and estimates are thus made regarding initial electricity demands for the area. The process in explained in detail in Appendix D.

To determine the impact of a driver on the electricity consumed, the change in said driver must be calculated from its initial value at time (t_0) to its value at the relevant time (t_i). The relative change in the driver can be calculate by dividing its value at the relevant time by its initial value as illustrated in Equation 45. When the relative value of the driver in known, it can be used to determine a change in the variable it is influencing. The extent to which a variable is affected by the driver is determined by elasticity.

Equation 45:

$$\text{Relative Driver Value } (\text{t}_\text{i}) = \frac{Driver\ Value(t_i)}{Driver\ Value(t_0)}$$

Numerous studies have been conducted regarding the elasticity of electricity demand. Most of these studies focus on price elasticity or output elasticity (of a given sector or the economy as a whole) (Bernstein & Griffin, 2006; Ziramba, 2008; Inglesi-lotz, 2011; Inglesi-lotz & Blignaut, 2011; Deloitte, 2012; Blignaut, Inglesi-lotz & Weideman, 2015). The results varied significantly between the studies, depending on the method used to calculate elasticity and the period over which elasticity was calculated.

Electricity demand in the residential sector is said to be impacted by population, GDP per capita and the price of electricity. These impacts can be confirmed by Kebede *et al.* (2010) who claims that per capita energy consumption correlates well with human development index (which is an indication of a country's social well-being, development and living standards). The study also indicates a positive correlation between population growth rates and energy demand. Ziramba (2008) also reports a statistically significant price elasticity, specifically for residential electricity consumption. In theory, as household income increases, people are able to rise their standard of living and buy appliances that consume electricity. This leads to increased household electricity consumption. Household income would thus be able to give a more accurate and less generalised indication of residential electricity consumption than GDP or even GDP per capita. However, household income is more difficult to estimate over the long run and thus real GDPR per capita (real regional gross domestic product per capita) is used in the model.

Expanding Equation 40 then, the effect of GDPR per capita on residential electricity demand is calculated using relative real GDPR per capita (RRGPC) raised to the exponent of GDPR per capita elasticity of demand (GPCED) (see Equation 46). An elasticity of GDPR per capita of 0.31 is used as reported by Ziramba (2008). As is expected, the elasticity has a positive sign, indicating that electricity demand will increase as GDPR per capita increases. Because the elasticity is in the 0 to 1 range, it can be considered as inelastic.

Equation 46:

$$EGPC(t) = RRGPC(t)^{(GPCED)}$$

The effect of electricity price (EPE) for residential demand was calculated by raising the relative real price of electricity ($RREP$) (for residential consumers) to the exponent of price elasticity of demand (PED) (see Equation 47). Ziramba (2008) reports a price elasticity of -0.04 for residential electricity consumption. The value of residential price elasticity indicates that it is inelastic. Thus an increase in price is not likely to have a major impact on residential electricity consumption. Intuitively, one can argue that the demand for residential electricity decreases with an increase in price due to efforts to make electricity use more efficient (buying energy saving appliances) and consumers behaving less wasteful. It should however be noted that price elasticity of up to -1.35 is also encountered in literature, but this study focused purely on prepaid users (Anderson, 2004).

Equation 47:

$$EPE_i(t) = RREP_i(t)^{(PED_i)}$$

Finally the population effect on electricity demand is described by Equation 48, where the relative population (RP) is raised to the exponent of the population Elasticity of demand ($PopED$). Intuitively, as the population increases, electricity demand will also increase (ignoring general changes in electricity efficiency). However, data on the exact population elasticity of electricity demand could not be found. It is thus assumed to be unit elastic ($PopED = 1$), following the assumption of work by Oosthuizen (2016).

Equation 48:

$$PE_i(t) = RP(t)^{(PopED_i)}$$

Electricity demand in the local government sector is assumed to be driven by population and electricity price. The effect of population on electricity demand is similar to that of residential sector and thus Equation 48 was used again. As the municipal area's population grows, so does the water and wastewater treatment requirements. As towns expand to accommodate the increased population, more street lighting is required as well as other services offered by local government that require electricity. The increased electricity demand is expected to be inelastic. A population elasticity of demand was assumed to be 0.03, since no credible data could be found to suggest otherwise. Data on the price elasticity of demand could also not be found for local government. Using Equation 47 to calculate the effect of electricity price, a value of -0.04 was assumed for price elasticity (equal to the residential price elasticity of demand). Anderson (2004) states that both income and price elasticity of demand are highly dependent on the area in which elasticity studies are conducted. Even across South Africa's provinces, household electricity consumption varies. The values used in this study is from literature that focused on the whole of South Africa. Regional elasticity values in all cases will in reality be different from the values used in this study.

The focus of literature studies indicated that the main drivers for electricity consumption in economic sectors (agriculture, commercial and industrial) tend to be electricity price and output (in term of GDP). Equation 47 was used to calculate the electricity price effect (EPE) for the agriculture, commercial and industrial sector (which are grouped together under a single "business" sector). Many literature sources follow an aggregate approach when determining price elasticity of demand (Inglesi, 2010; Inglesi & Pouris, 2010; Inglesi-lotz, 2011; Deloitte, 2012). The majority of these sources also focus their investigation on the period of 1980 – 2005, before the major Eskom price hikes started in 2008. These factors make it difficult to compare price elasticity values with those found in literature that follow a disaggregate approach or focus on a more recent period. For a summary of price elasticity found in literature (both South Africa and Internationally) Blignaut *et al.* (2015) can be consulted. The model assumes a value of -0.26 for the price demand elasticity of businesses. The value is based on each sectors approximate contribution to Hessequa's economy. The following elasticity values are found in literature:

- Agriculture: -0.235 (Blignaut *et al.*, 2015).
- Commercial: -0.19 (Blignaut *et al.*, 2015).
- Industrial: -0.869 (Inglesi-lotz & Blignaut, 2011).

As expected, price elasticity of demand for all the sectors are negative and inelastic, indicating a reduced demand as electricity prices increase. A probable explanation for this behaviour is that more effort is put into energy efficient solutions as electricity prices increase. Before Eskom's major price hikes following the electricity supply crisis of 2008, electricity was relatively cheap. Blignaut and others (2015) report that electricity price elasticity in most economic sectors to be insignificant for the period 2002 – 2007. From 2008 – 2012 however, all sectors (aside form gold and platinum mining) show statistically significant sensitivity to electricity price.

The GDPR effect ($EGDPR$) for the business sector is calculated using Equation 49. Relative real regional GDP is raised to the exponent of GDP elasticity of demand ($GDPED$). The following elasticity values are found in literature (Inglesi-lotz & Blignaut, 2011):

- Agriculture: 0.032.
- Commercial: 0.767.
- Industrial: 0.712.

Elasticity is thus estimated as 0.64, based on the weighted average contribution of each sector to Hessequa's economy (similar to the approach used for price elasticity of demand). GDP elasticity for all sectors are positive and inelastic. Logically this makes sense since more production will usually require more energy (ignoring efficiency efforts). It should be noted that the elasticity values used for each sector does not distinguish between the different sub-sectors of commercial and industrial activities or the various types of agriculture. Demand elasticity will vary depending on the type of activity because energy intensity will vary from one type of commercial, industrial or agricultural activity to the next.

Equation 49:

$$EGDPR_i(t) = RRGDPR(t)^{(GDPED)}$$

4.2.10 Population sub-model

Population growth and fertility rates are affected by multiple factors. When immigration and emigration rates are low, fertility rates are a main driving force for population growth. Fertility rate is influenced by a number of factors such as gender division of labour, the level of healthcare, income and education levels, economic and employment uncertainties, fertility preferences, socioeconomic status, the cost of having children, cultural contexts, religious views, government policy measures, contraceptive and reproductive technologies and demographics like age structure and infant mortality rates (Balbo, Billari & Mills, 2013; Jackson, 2013). For much of the 20th century is observed that areas with relatively low levels of economic development have higher fertility rates compared to areas that are economically more developed (Fox, Klüsener & Myrskylä, 2015). Death rate is typically influenced by access to healthcare facilities, the average standard of living, prevalence of infectious disease, nutrition and access to drinking water. Conflicts or high levels of violent crime will also have an impact on death rates. It would be impractical to include all of these factors into the model because the impact of each factor is difficult to determine. Therefore the model is kept relatively simple and configured to conform to current population predictions.

The population sub-model predicts Hessequa's population between 2017 and 2040. Hessequa's initial population is assumed to be 58 486 people (extrapolated from 2014 population and population growth rate (Hessequa Municipality, 2014)). The main factors that influence population growth are births, deaths and migration. According to the latest available data (Western Cape Government, 2013d) death rate (all causes) for the Hessequa Municipality in 2010 was 816/100 000 people per year. A death rate of 0.816% was thus assumed and kept constant over the modelling period. The number of annual deaths are calculated using Equation 50.

Equation 50

$$Deaths(t) = Population(t) \times Death\ Rate$$

Regarding migration into and out of Hessequa, data could only be found on immigration. According to Hessequa Munuicipality (2013), a total of 8750 people moved into Hessequa. The period over which this migration took place is not explicitly specified, but it is assumed to be from 2001 to 2011. That amounts to an average of 875 people per year. Migrants expressed as a percentage of the 2011 population (52 642 people (StatsSA, 2011)) was 1.662%. A migration rate of 1.4% is thus assumed to account for emigration as well. The net migration rate is assumed to remain constant for the period being modelled in this work. Net migration is calculated using Equation 51.

Equation 51

$$Net\ Migration(t) = Population(t)\ \times\ Average\ Migration\ Rate$$

Since only the female portion of the population contributes to births, this is also factored into the model. Hessequa's gender distribution in 2011 was 51.3% women (StatsSA, 2011), equal to a female population fraction ($F_{Females}$) of 0.513. This is assumed to be constant for the modelling period. Hessequa's female population is calculated using Equation 52. The number of births each year is determined by multiplying the female population with a crude birth rate as expressed in Equation 53. A crude birth rate of 1.8 % is used in the model. Equation 54 is used to calculate Hessequa's population, which is modelled as a stock.

Equation 52

$$Female\ Population(t) = Population(t) \times F_{Females}$$

Equation 53

$$Births(t) = Female\ Population(t) \times Crude\ Birth\ Rate$$

Equation 54

$$Population(t) = \int_{t_0}^{t}[Births(s) - Deaths(s) + Net\ Migration(s)]ds + Population(t_0)$$

As part of the population sub-model, the number of households in Hessequa is also calculated. It is assumed that there is an average of 3.3 residents per household (Hessequa Municipality, 2014). The number of households is then calculated by dividing population by the average number of residents per household (see Equation 55).

Equation 55

$$Housholds(t) = \frac{Population(t)}{Average\ residents\ per\ household}$$

4.2.11 Regional gross domestic product sub-model

Hessequa's economy is briefly discussed in Section 3.1. Real GDPR is modelled as a stock with an initial (2017) value of R 3.042 250 Billion. This figure is extrapolated from the latest available GDPR data, assuming a real annual GDPR growth rate of 2.44%. The 2.44% is reported to be Hessequa's average long term growth rate (Hessequa Municipality, 2017).

Real GDPR is modelled as a stock and calculated using Equation 56. It is assumed that building Hessequa's renewable energy generation capacity would have a positive impact on the regional gross domestic product. However, this was not included in the model as the impact is considered be negligible.

Equation 56

$$Real\ GDPR(t) = \int_{t_0}^{t} [Real\ GDPR\ Growth(s)]ds + Real\ GDPR(t_0)$$

The model calculates real GDPR per capita by dividing real GDPR by Hessequa's population (see Equation 57).

Equation 57

$$Real\ GDPR\ per\ capita(t) = \frac{Real\ GDPR(t)}{Population(t)}$$

Relative real GDPR (Equation 58) and relative real GDPR per capita (Equation 59) are more robust measures of economic development. 2017 is used as a base year for both indicators to measure future economic development in the municipal area, relative to the base year.

Equation 58

$$Relative\ Real\ GDRP(t) = \frac{Real\ GDRP(t)}{Real\ GDRP_{Base\ Year}}$$

Equation 59

$$Relative\ Real\ GDRP\ per\ capita(t) = \frac{Real\ GDRP\ per\ capita(t)}{Real\ GDRP\ per\ capita_{Base\ Year}}$$

4.2.12 Employment sub-model

Unemployment is a big problem in all of South Africa. By building renewable electricity capacity locally, positive socio-economic impacts regarding job creation are expected. The model distinguished between construction, manufacturing and installation (CMI) jobs and operation and maintenance (O&M) jobs.

Generally CMI jobs only exist during the time a new RE facility is under construction. Jobs categorised under CMI involve all employment from where the components are manufactured through to the commissioning of the new RE facility. The CMI phase of a project requires a large labour force and is mostly short term based. Due to the relatively small market for renewable technologies in the near and medium term future and the high skill levels required in this phase, it is assumed that all CMI jobs would be the responsibility of agents outside the Hessequa area. As a result, these jobs would not directly impact unemployment in the Hessequa area. The O&M phase of a RE project is less labour intensive, requiring only a few operators and maintenance personnel. The jobs created in this phase of an RE project are long term based. It is assumed that Hessequa's local human capital would be developed to fill O&M job opportunities. Socio-economic benefits can then be experienced through local skills development and a slightly reduced unemployment rate.

To calculate the number of O&M jobs ($Jobs_{O\&M}$) the model multiplies each RET's operational generating capacity (GC) with a multiplier for O&M jobs ($F_{J_{O\&M}}$) (see Equations 60). A similar equation is used for calculating the number of CMI jobs ($Jobs_{CMI}$). The multiplier used for CMI jobs is denoted as $F_{J_{CMI}}$ in Equation 61. Due to advances in manufacturing and construction processes as well as increased automation regarding the operation of facilities, the number of jobs created per MW of generation capacity is likely to decrease in the future (Rutovitz & Atherton, 2009). Such factors are however not included in the model and job multipliers (see Table 9) are assumed to remain constant for the duration of the model period.

Equation 60:

$$Jobs_{O\&M\ RET,i}(t) = F_{J_{O\&M,i}} \times GC_{RET,i}(t)$$

Equation 61:

$$Jobs_{CMI\ RET,i}(t) = F_{J_{CMI,i}} \times GC_{RET,i}(t)$$

Biomass power generation requires a constant source of fuel. Equation 62 is used to account for the jobs opportunities created during the fuel processing phase. To calculate the number of jobs created during fuel processing the biomass electricity generated ($EG_{Biomass}$) is multiplied by a fuel jobs factor ($F_{J_{Fuel}}$). It should be noted that the number of jobs created in fuel harvesting can vary greatly depending on the degree of mechanisation. For Hessequa, it is likely that the real number of fuel jobs will be higher than what the model predicts. This is due to a strong emphasis on job creation from government's perspective. Thus, a high degree of mechanisation will probably be discouraged.

Equation 62:

$$Jobs_{Fuel}(t) = F_{J_{Fuel}} \times EG_{Biomass}(t)$$

Values for the job factors are presented in Table 9. Values in the Total CMI, O&M and Fuel columns were used in the model.

Table 9: Jobs created in the renewable electricity sector. Source: Rutovitz (2010)

Technology	**CMI jobs**			**O&M and Fuel**	
	Total CMI	**Construction / Installation**	**Manufacturing**	**O&M**	**Fuel**
	Person years/MW			**Jobs/MW**	**Jobs/GWh**
Biomass	4.3	3.9	0.4	3.1	0.22
Pumped Storage	11.3	10.8	0.5	0.22	0
Wind	15.4	2.5	12.5	0.4	0
PV	38.4	31.9	9.1	0.4	0

The total number of non-local and local jobs created are calculated using Equation 63 and Equation 64 respectively. As stated, the fuel jobs and O&M jobs are assumed to be localised and CMI jobs are assumed to be non-local. The total number of jobs created is calculated using Equation 65.

Equation 63

$$Jobs_{Non-Local}(t) = \sum Jobs_{CIM\ RET,i}(t)$$

Equation 64

$$Jobs_{Local}(t) = \sum Jobs_{O\&M\ RET,i}(t) + Jobs_{Fuel}(t)$$

Equation 65:

$$Total\ Jobs\ (t) = Jobs_{Non-Local}(t) + Jobs_{Local}(t)$$

For the sake of comparing employment in the different RETs, the total number of jobs created for each technology is also calculated using Equation 66 (pumped storage, solar PV and wind power). Equation 67 is used to calculate the total number of jobs created using biomass technology. Jobs relating to rooftop PV are not included in the model.

Equation 66

$$Jobs_{RET,i}(t) = Jobs_{CMI,RET,i}(t) + Jobs_{O\&M,RET,i}(t)$$

Equation 67

$$Jobs_{Biomass}(t) = Jobs_{CMI,Biomass}(t) + Jobs_{O\&M,Biomass}(t) + Jobs_{Fuel}(t)$$

4.2.13 Emissions sub-model

Even though the Hessequa Municipality does not host any Eskom coal or gas fired generation capacity, the municipality is still dependant on Eskom for electricity. Therefore, Hessequa is responsible for the emissions caused when electricity used in the area is generated by Eskom. Hessequa can thus be considered responsible for the negative environmental impacts associated with its fossil fuel based electricity consumption. Although CO_2 is not the only greenhouse gas or pollutant emitted during electricity generation, it does account for the majority of GHG emitted during fossil fuel based electricity generation.

Even though most RETs have no direct CO_2 emissions it is incorrect to assume that these technologies are carbon neutral. During manufacturing and transportation of equipment used to construct RET installations, various processes are involved that use fossil fuel based electricity and transportation fuels. These indirect emissions can be accounted for using life-cycle CO_2 emissions. Each RET's electricity generation is multiplied with an emission factor ($F_{E_{CO_2},RET,i}$) to calculate the CO_2 emissions associated with the respective technologies ($CO_2\ Emissions_{RET,i}$). The emission factors used in Equation 68 are presented in Table 4 as part of renewable energy benefits. The median emissions are used in all cases.

Equation 68

$$CO_2\ Emissions_{RET,i}(t) = EG_{RET,i}(t) \times F_{E_{CO_2},RET,i}$$

Hessequa's Eskom supplied electricity relies heavily on fossil fuel generation. Eskom reports an average emission factor in its integrated report of 1.01 $kg\ CO_2/kWh$ (Eskom, 2015b). This emission factor will decreased slightly as more renewable and nuclear power is added to the national grid in the future. The decrease in Eskom's emission factor is assumed to be linear over the modelling period. It is assumed to reach 0.97 $kg\ CO_2/kWh$ in 2040. Eskom related electricity emissions are determined using Equation 69.

Equation 69

$$CO_2\ Emissions_{Eskom}(t) = \ EG_{Eskom}(t)\ \times\ F_{E_{CO_2},Eskom}(t)$$

In Equation 70, Hessequa's total annual electricity related CO_2 emissions ($CO_2\ Emissions_{Annual}$) are calculated. The emissions from all renewable sources are summed together and added to emissions resulting from Eskom electricity consumed within Hessequa. Cumulative CO_2 emission ($CO_2\ Emission_{Cum}$) is modelled as a stock to measure the long term environmental impacts of implementing RET. It is calculated using Equation 71.

Equation 70

$$CO_2\ Emission_{Annual}(t) = \sum CO_2\ Emissions_{RET,i}(t) +\ CO_2\ Emissions_{Eskom}(t)$$

Equation 71

$$CO_2\ Emission_{Cum}(t) = \ \int_{t_0}^{t}[CO_2\ Emissions_{Annual}\ (s)]ds + CO_2\ Emission_{Cum}(t_0)$$

The impacts of carbon dioxide emission reductions will not be directly visible in Hessequa. These reductions should rather be viewed as Hessequa's contribution towards South Africa's fight against climate change.

4.2.14 Electricity sector water demand sub-model

All electricity generation technologies require water to a greater or lesser extent throughout their life-cycle. Because of this, the power sector might be vulnerable to constraints during periods of drought or water scarcity (Meldrum, Nettles-Anderson, Heath & Macknick, 2013). Extensive information is available in literature regarding the water requirements of different generation technologies. While the term "*water use*" is often used generically, a distinction can be made between water withdrawal and water consumptions of the different technologies. Meldrum and others (2013) define water withdrawal as water being diverted from a surface-water source or removed from a groundwater source for use. Water consumption is defined as water withdrawn but not returned to the immediate water environment.

Regarding biomass power generation, the specific technology used for generation, the biomass crops and production methods will all impact water requirements (Meldrum *et al.,* 2013). The cooling method employed will also impact the water requirements in thermal biomass generating technologies. All these variables complicates estimating water requirements for biomass power. The model uses the median values reported for biomass power in Table 10.

Accounting for water requirements in hydropower or pumped storage is also challenging due to evaporation from reservoirs (which will vary depending on ambient temperature, surface area of the reservoir (Evans, Strezov & Evans, 2009)) and the definition of water use in each case. According to Meldrum and others (2013), literature reports values ranging from 0 to 18 000 gal/MWh (68 137 l/MWh). Water consumption of hydropower is used for pumped storage since no data could be found referring specifically to pumped storage.

RETs such as wind turbines and solar PV panels do not require cooling like other thermal methods of electricity generation. During the operation phase, solar PV systems might require occasional washing which requires water, but wind turbines require very little (if any water) for cleaning. Table 10 presents a summary of the common ranges and median values for electricity generation water consumption. The mean water consumption values are used in the model.

Table 10: Water consumption of renewable electricity technologies. Source: Meldrum and others (2013), Macknick, Newmark, Heath and Hallett (2011)

Technology	Water consumption (l/MWh)		
	Min	Median	Max
Wind	0.4	3.8	34.1
Solar PV	37.9	306.6	794.9
Biomass power	1022.1	1145.5	1525.5
Pumped storage	5394.2	17000.3	68137.4

Using the water consumption values in Table 10, the water demand (WD) for each renewable technology is calculated by multiplying each RET's electricity generation (EG) by that technology's water consumption per unit of generation ($\widehat{WC}$) (see Equation 72).

Equation 72:

$$WD_{RET,i}(t) = EG_{RET,i}(t) \times \widehat{WC}_{RET,i}$$

Due to the high uncertainty and extremely high water requirements of pumped storage compared to the other RETs, RE water demand is calculated for the total of all RET (Equation 73) and again where pumped storage is excluded from the calculation (Equation 74).

Equation 73:

$$WD_{Total\ incl.\ Pumped\ Storage} = \sum WD_{RET,i}$$

Equation 74

$$WD_{Total\ excl.Pumped\ Storage}(t) = WD_{Utility\ Solar\ PV}(t) + WD_{Biomass}(t) + WD_{Utility\ Wind}(t)$$

The accumulated water consumption ($Water\ Cons$) in each case (including and excluding pumped storage) is then calculated using Equation 75 and Equation 76 respectively.

Equation 75

$$Water\ Cons_{NonHydro\ RE}(t) = \int_{t_0}^{t}[WD_{NonHydro\ RE}(s)]ds + Water\ Cons_{NonHydro\ RE}(t_0)$$

Equation 76

$$Water\ Cons_{Total\ RE}(t) = \int_{t_0}^{t}[WD_{Total\ RE}(s)]ds + Water\ Cons_{Total\ RE}(t_0)$$

4.2.15 Investment in renewable electricity sub-model

Various instruments are used for financing projects during the REIPPPP bidding rounds up to date. Many international and domestic project developers invested, as well as equity share holders and sponsors. Insurers, banks (Standard Bank, Nedbank, ABSA, DBSA, RMB, and Investec), international utilities (Enel form Italy) and development finance institutions are also involved. Project finance, corporate finance, debt funding, and funding from insurance and pension funds are all utilised in renewable energy projects (Eberhard *et al.*, 2014).

The renewable energy capital cost in project finance is often structured on a 70:30 to 80:20 basis of debt to equity ratio. The debt financing is provided by lenders on fixed loan terms. They carry no liability for losses incurred in the project and thus their risk is relatively small. These lenders also receive the first revenue generated by a project. On the other hand, equity investors face greater risks as they are depending on the project to be successful before they can receive a return on their investment. Due to the added risk that equity investors face, they expect a bigger return on investment (ROI) than debt financiers. This translates into the following: A larger debt share results in lower project funding costs. This also means that lower tariffs are possible for the generated electricity. The average cost of debt during the REIPPPPP was 12% per year for a 20 year period, compared to European RE projects that usually have interest rates of 7% over a 10 – 15 year term (Baker, 2015).

The REIPPPP has many additional requirements like minimum levels of South African entity participation, black economic empowerment and community ownership. Baker (2015), reports that many international companies are not interested in investing due to these additional project requirements. Because renewable energy in Hessequa will not necessarily be part of a REIPPPP project, these criteria might not apply.

Eberhard and others (2014) state that private financiers and sponsors are willing to make renewable energy investments on the conditions that a transparent, well designed procurement process is in place and that projects are reasonably profitable, with mitigated risks.

The investment sub-model used in HessREM is largely based on the structure of WeCaGEM, presented in Oosthuizen (2016). The model contains a policy option where decision makers can select the fraction of each RET ($REGGG\ Fill\ Fraction_{RET,i}$) used to fill Hessequa's renewable energy generation goal gap ($REGGG$). Based on the policy decision, the sub-module first determines how much electricity generation is required from each RET ($New\ Build\ Generation\ Demand_{RET,i}$) (Equation 77).

Equation 77

$$New\ Build\ Generation\ Demand_{RET,i}(t) = REGGG(t) \times REGGG\ Fill\ Fraction_{RET,i}$$

A capacity conversion factor ($F_{CC\ ,RET,i}$), specific to each technology, is then used to calculate the generation capacity required to meet each technology's new build generation demand (Equation 78). The model then calculates the investment required for the new generation capacity by multiplying the new build capacity demand by the capital cost of each technology ($CC_{RET,i}$) (Equation 79). The total new build investment that is required ($TNBIR$) is calculated by summing the required investments of each technology (Equation 80).

Equation 78

$$New\ Build\ Capacity\ Demand_{RET,i}(t) = F_{CC,RET,i} \times\ New\ Build\ Generation\ Demand_{RET,i}(t)$$

Equation 79

$$New\ Build\ Investment\ Required_{RET,i}(t) =\ CC_{RET,i}(t) \times\ New\ Build\ Capacity\ Demand_{RET,i}(t)$$

Equation 80

$$TNBIR(t) =\ \sum New\ Build\ Investment\ Required_{RET,i}(t)$$

Presumably there will not be enough funds available each year to meet the total new build investment requirement. To address this issue, the available funds will be split between technologies based on an available funds allocation fraction ($AFAF_{RET,i}$), calculated by Equation 81.

Equation 81

$$AFAF_{RET,i}(t) = \frac{New\ Build\ Investment\ Required_{RET,i}(t)}{TNBIR(t)}$$

Investment funds could come from various sources as already stated. The business model behind this might be a private – public partnership that includes the municipality or a different approach can be followed. The details of this matter is beyond the scope of this work. For modelling purposes, it is assumed that a fraction of regional gross domestic product will be invested in RET each year (if the renewable energy generation goal gap requires it). This investment fraction can be determined by decision/policy makers. The renewable energy investment funds ($REIF$) that will be available to expand Hessequa's generation capacity is determined by Equation 82. An "IF THEN ELSE" statement was used to prevent the allocation of funds to renewable energy technologies during 2017. It was assumed that any recommendations made by the model will not take effect before start of the following year (2018). The actual investment into each RET ($Investment_{RET,i}$) is calculated by multiplying the $REIF$ by each technology's allocation factor (Equation 83).

Equation 82

$$REIF(t) = GDPR\ Investment\ Fraction \times Real\ GDPR(t)$$

Equation 83

$$Investment_{RET,i}(t) = REIF(t) \times AFAF_{RET,i}(t)$$

Finally, the total annual RET investment ($TRETI$) is calculated by summing the annual investment into different RETs (Equation 84). The accumulated RET investment ($Acc.RETI$) is also calculated to estimate the total investment into RETs over the modelling period (Equation 85).

Equation 84

$$TRETI(t) = \sum Investment_{RET,i}(t)$$

Equation 85

$$Acc.RETI(t) = \int_{t_0}^{t} [TRETI(s)]ds + Acc.RETI(t_0)$$

4.2.16 Impacts on the municipality sub-model

To ensure fairness, it was assumed that the municipality would compensate the owners of rooftop PV systems that feed electricity back into the local grid. The compensation for rooftop PV ($RPVC$) owners was calculated by multiplying the rooftop PV electricity fed back into the grid with the real cost of rooftop PV electricity and a feed-in-tariff factor (F_{FIT}) (Equation 86). This feed-in-tariff factor is used to vary the compensation for rooftop PV electricity. In reality the municipality could choose any rate to compensate those who feed electricity back into the grid. They could also decide not pay anything at all. In the simulation scenarios, this feed-in-tariff was used to incentivise the installation of embedded generation.

Equation 86

$$RPVC(t) = EG_{Rooftop\ PV\ Grid}(t) \times REC_{Rooftop\ PV}(t) \times F_{FIT}$$

As discussed in section 4.2.8, the real ($REC_{Hessequa}$) and relative real cost of grid connected electricity ($RREC_{Hessequa}$) are calculated in the model. This real electricity cost is assumed to only apply to the municipality.

To estimate the cost of electricity that customers will pay ($RETariff_{Hessequa}$), a municipal mark-up (46.09%) is added to the real cost of Eskom electricity (see Equation 87). This is considered a reasonable assumption for the following reasons:

- In most cases the cost of renewable electricity is predicted to fall. If Hessequa can buy electricity directly from an IPP at a price that is lower than Eskom's and still sell that electricity at their normal tariff, it would increase their profits.
- These increased profits can then be used to subsidise other municipal functions and mandates or to improve service delivery.
- The profits can also be used to encourage the uptake of embedded generation by paying a higher feed-in-tariff.

Equation 87

$$RETariff_{Hessequa}(t) = REC_{Eskom}(t) \times (1 + Markup)$$

Hessequa's relative real electricity tariff ($RRETariff_{Hessequa}$) is calculated in Equation 88, and used to impact electricity demand of the residential and business sectors (see section 4.2.9).

Equation 88

$$RRETariff_{Hessequa}(t) = \frac{RETariff_{Hessequa}(t)}{Initial\ RRETariff_{Hessequa}}$$

One of the municipality's main concerns regarding rooftop PV installations is the municipality's loss in electricity revenue. The model attempts to capture this dynamic as well. Section 4.2.6 describes how much rooftop PV electricity is generated and how much of it is fed into the grid. The difference between these two values will then be equal to how much rooftop PV electricity is consumed on site ($EG_{Rooftop\ PV,Own\ Use}$), presumably by the owners of these installations. This on-site electricity consumption is determined by Equation 89.

Equation 89

$$EG_{Rooftop\ PV,Own\ Use}(t) = EG_{Rooftop\ PV}(t) - EG_{Rooftop\ PV\ Grid}(t)$$

To determine how much of its gross profit the municipality will lose ($MGPL$) from electricity sales (due to rooftop PV installations) the on-site rooftop PV electricity use is multiplied with the gross profit per kWh. This is the gross profit the municipality receives from its electricity sales (Equation 90). Should the municipality indeed decide to compensate rooftop PV electricity being fed into the grid, they will experience a double negative financial impact. This total financial impact of rooftop PV ($TFIRPV$) will be equal to the sum of the lost revenue and the rooftop PV compensation (Equation 92).

Equation 90

$$Gross\ profit\ per\ kWh(t) = RETariff_{Hessequa}(t) - REC_{Hessequa}(t)$$

Equation 91

$$MGPL(t) = Gross\ Profit\ per\ kWh(t) \times EG_{Rooftop,Own\ Use}(t)$$

Equation 92

$$TFIRPV(t) = MGPL(t) + RPVC(t)$$

The amount of electricity bought by the municipality for resale ($EBMR$) is equal to end user electricity demand of the business sector and the residential sector. As mentioned, a certain portion of the residential sector demand is met with embedded generation. This is accounted for in Equation 93. Local government buys electricity at the real cost of Hessequa electricity (the weighted average cost of all electricity being supplied). Local government then resell that electricity at the marked-up price (the real Hessequa electricity tariff). Local government's gross profits ($Gross\ Profit_{Electricity\ sales}$) from electricity sales as well as the gross profit margin ($Gross\ Profit\ Margin_{Electricity\ sales}$) can then be calculated from Equations 94 to 97.

Equation 93

$$EBMR(t) = EUED_{Residential}(t) + EUED_{Business}(t) - EG_{Rooftop\ PV,Own\ Use}(t)$$

Equation 94

$$Cost\ of\ electricity\ bought\ for\ resale(t) = REC_{Hessequa}(t) \times EBMR(t)$$

Equation 95

$$Electricity\ sales\ income(t) = EBMR(t) \times RETariff_{Hessequa}(t)$$

Equation 96

$$Gross\ Profit_{Electricity\ sales}(t) = Electricity\ sales\ income(t) - \\ Cost\ of\ electricity\ bought\ for\ resale(t)$$

Equation 97

$$Gross\ Profit\ Margin_{Electricity\ sales}(t) = \frac{Gross\ Profit_{Electricity\ sales}(t)}{Electricity\ sales\ income(t)}$$

4.2.17 HessREM settings

The timeframe for HessREM is set from 2017 to 2040. This period is chosen because the model's purpose is to serve as a planning tool for Hessequa's renewable energy future. Renewable energy technology is rapidly improving. Technology used today might be rendered obsolete in the next 20 years. There is also a great deal of uncertainty regarding Eskom's future. Many of the trends expressed in the model might change over time. Modelling beyond a 2040 horizon can be considered pure speculation and will therefore not add much value to the model. Figure 14 can be consulted for more details regarding the model settings.

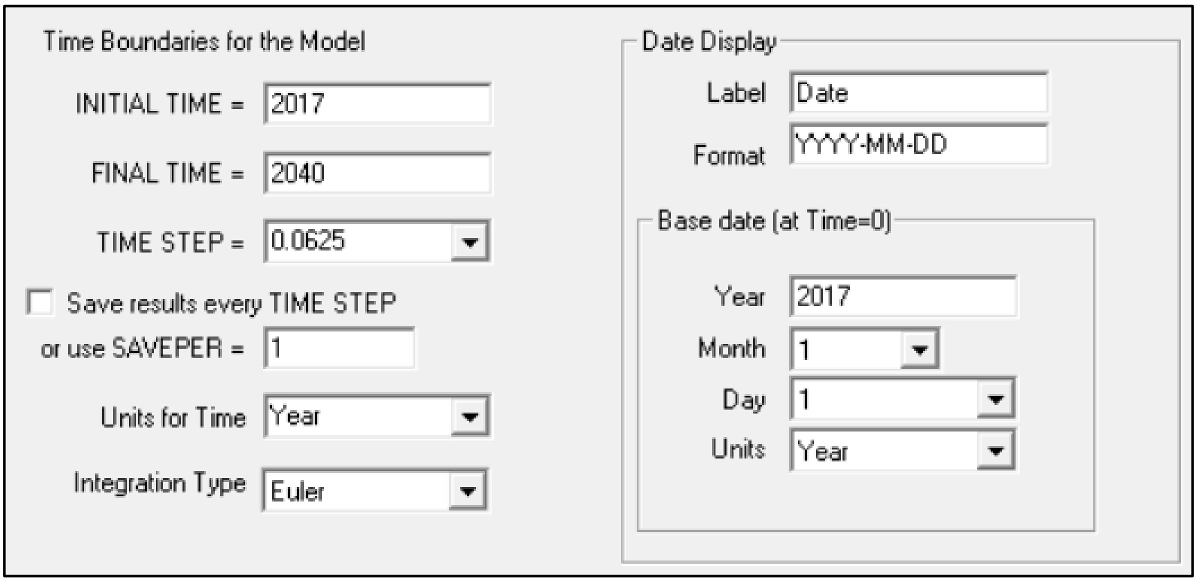

Figure 13: HessREM settings used in simulations

4.3 Data Collection for Modelling

Data is collected from various sources ranging from published academic papers, integrated development plans, reports and interviews with field experts and Hessequa Municipality officials. Due to the relatively low level of the project, data specific to the municipal area is not always available. In these cases, district, province or national level data is used or assumptions are made. The major sources of data and information used in the model parameters are identified in Tables 11.

Table 11: Model parameter data sources – part 1

Sub-model	Source
Biomass Power	Centre for Climate and Energy Decision Making (2015), Department of Energy (2015b), REN21 (2015), NREL (2016), SAEON (2016)
Biomass Fuel	Morokong, Blignaut, Nkambule, Mudhavanha and Vundla (2016), SANEDI (2016)
Wind Power	Centre for Climate and Energy Decision Making (2015), NREL (2016), Siemens (2017), The Royal Academy of Engineering (2017)
Solar PV Power	El Chaar, Lamont and El Zein (2011), MINES ParisTech (2016), NREL (2016), Photovoltaic software (2016)
Pumped Storage	Centre for Climate and Energy Decision Making (2015), REN21 (2015), NREL (2016)
Rooftop Solar PV	MINES ParisTech (2016), Photovoltaic software (2016)
Electricity Supply	Hessequa Municipality (2016), Lesch (2017b)
Electricity Demand	Ziramba (2008), Inglesi-lotz and Blignaut (2011), Blignaut *et al.* (2015), Hessequa Municipality (2016), Oosthuizen (2016), Lesch (2017b)
Electricity Price	South Africa - Department of Energy (2015), GreenCape (2016)
Electricity sector Water Demand	Macknick *et al.* (2011), Meldrum *et al.* (2013)
Investment in Renewable Electricity	N/A
Gross Domestic Product by Region	Hessequa Municipality (2017)
Emissions	IPCC (2014), Eskom (2016a)
Employment	Rutovitz (2010)
Population	StatsSA (2011), Western Cape Government (2013d), (Hessequa Municipality, 2014), UNDP (2016a)

4.4 Model Validation

Models need to be validated before they can be used. There needs to be a sufficient degree of soundness and usefulness in models (Maani & Cavana, 2012). The purpose of the model has to be specified before it can be evaluated for its usefulness and the degree to which a model is considered to be useful might also be different depending on the audience evaluating it (Forrester & Senge, 1980). Since there are informal, subjective and qualitative aspects to the validation process, it cannot be considered to be entirely objective (Barlas, 1994).

No single test can be used to fully validate a system dynamics model (SDM). SDM is also criticised for its lack of formal validation tools (Barlas, 1994). The model validation should rather be seen as a process where confidence is built in the model by passing various validation tests. Validation tests used in other types of models, like standard statistical hypothesis tests are usually not appropriate for SDM type models (Forrester & Senge, 1980).

Various authors outline a series of tests (that are more appropriate to SDM) to assist in model validation. Coyle (1983) suggests three main categories of test, namely: verification, validation and legitimation tests.

- Verification tests are designed to ensure that structures and parameters in the model has been correctly transcribed from the real system it is meant to represent.
- Validation test are focused on the model's behaviour. These tests are used to determine if the model generates results that could be expected from the real system.
- Legitimation tests are conducted to determine if generally accepted rules as well as the laws of the system structure are obeyed.

Later work by Coyle (1996) involve a series of guidelines to aid in building model confidence. These are as follows:

- CLDs must correspond to the problem statement.
- Equations in the stock and flow models must correspond to the influence signs in the CLDs.
- The model must be dimensionally sound.
- No unrealistic values must be produced (negative births, negative physical quantities, etc.).
- Conservation of flow should be maintained (similar to the conservation of mass or energy in a physical system).
- All equations used in the model must be fully justified or documented (e.g. relationships between certain variables).
- The model should demonstrate the proper behaviour when subjected to extreme condition testing

Forrester and Senge (1980) describe 17 tests for model verification. These tests are organised based on their area of focus, namely: model structure tests, model behaviour tests and tests that handle policy implementation. Performing all 17 of these tests would be tedious and time consuming and not all of them might be appropriate for a given model. They therefore highlight what is considered to be "core" tests for a system dynamics model. The tests they propose are summarised in Table 12.

Table 12: Confidence-building tests for system dynamics models. Source: Maani and Cavana (2012), Qudrat-Ullah (2012), Forrester and Senge (1980)

Validation test	**Description**
Structure tests	
Structure verification	Does the structure of the real system compare well with the structure used in the model?
Parameter verification	Do parameters in the model correspond to those in the real system, both conceptually and numerically?
Extreme conditions	Does the model still demonstrate logical behaviour when extreme values are assigned to selected parameters?
Boundary adequacy	Are the relevant structures for addressing policies included and endogenous to the model?
Dimensional consistency	Are all equations in the model dimensionally consistent?
Behaviour tests	
Behaviour reproduction	Do the results generated by the model match observations from the real system relatively well?
Behaviour anomaly	Can particular model assumptions be defended when model behaviour changes occur when the said assumption is also changed?
Behaviour sensitivity	Could possible shifts in certain model parameters cause the model to fail previously passed behaviour tests?
Policy implementation tests	
Changed-behaviour prediction	Does the model predict the correct behavioural changes in the system, should a policy governing that system be changed?
Policy sensitivity	To what extent will policies recommended by the model be influenced by uncertainty in selected model parameters?

Barlas (1994) emphasises that structure validation tests should be carried out before behaviour validation since any behaviour validation test would only be meaningful if there is already sufficient confidence in the model's structure.

Conventionally, most formal model validation activities are conducted after the model has been completed. Thereafter, policy design simulations can proceed (Barlas, 1994).

4.4.1 Structure verification

The first step in model validation is identifying the appropriate model structure (Qudrat-Ullah, 2005). Structure verification determines whether or not the modelled system's structure adequately resembles the real system (Maani & Cavana, 2012). Structural verification is largely a qualitative process. To ensure the correct system structure is used during simulations, a qualitative description of the system was first developed in the form of a CLD (see section 4.1). The CLD was developed from stakeholder engagements (Kruyshaar, 2015) and qualitative system descriptions (Tshehla, 2014). The stock-and-flow model was developed from this CLD as well as other work that focused on system dynamics modelling in the energy sector, such as SAGEM (UNEP, 2013) and WeCaGEM (Oosthuizen, 2016). A detailed description of the system and the development process is presented in section 4.2. Input from this study's modelling supervisor was also used to ensure the qualitative model adequately resembles the real system. Causal relationships and equations used in the model were also compared to those used in SAGEM and WeCaGEM to ensure their correctness.

4.4.2 Parameter verification

The purpose of the parameter verification test is to determine whether or not the parameter values used in the model are consistent with knowledge of the system (Qudrat-Ullah, 2005). Sterman (2000) recommends the same basic guidelines for parameter verification as those used in structure verification, namely: comparing the parameter values with those found in the real system.

Literature data was used for parameter values whenever possible. The parameter data sources are identified in the Data Collection section (section 4.3). When no parameter data was available, expert opinion was used or parameter values were estimated within a plausible and reasonable range.

4.4.3 Extreme condition testing

According to Forrester and Senge (1980), much of our knowledge of the real system can be attributed to the system's performance under extreme conditions. Incorporating this knowledge of extreme conditions will, in most cases, yield an improved model under normal operating conditions. Forrester and Senge (1980) further state that extreme conditions tests may help to reveal omitted variables, finding structural flaws and explore policies that force a system to behave outside historical operating ranges.

Extreme condition test are performed by subjecting the system to a "shock". This shock can be in the form of a step or pulse function in certain variables, or by dramatically changing the values of certain model parameters. To pass an extreme condition test, the model must exhibit logical behaviour when subjected to extreme conditions (Qudrat-Ullah, 2005).

It is useful to have a reference case to compare with the results of extreme condition tests. For the extreme condition tests performed in this section, a reference case was used with the following assumptions regarding renewable energy investment:

- GDPR investment fraction was set to 1.5%
- Feed-in-Tariff (rooftop PV compensation) was set to 0.5
- Renewable Energy Generation Goal Gap Filled Fractions were set as follows:
  - Solar PV: 0.4.
  - Wind Power: 0.2.
  - Biomass Power: 0.3.
  - Pumped Storage: 0.1.

System aspects that were subjected to extreme conditions include the total end user electricity demand, the renewable energy generation goal gap and Hessequa's total renewable energy power capacity. In some cases variables were tested by introducing either a 10 fold step increase between 2022 and 2027 or a 10 fold initial increase in the variables that influence them.

A ten-fold step increase was introduced to crude birth rate for the period 2022 – 2027 and the impact on population was investigated. As expected, population increased dramatically in the period where crude birth rate increased and continued to grow at rates comparable to population growth before the step increase was introduced (see Figure 45 in Appendix G).

The impact of a tenfold step increase in the real GDPR growth rate was also tested for the period 2022 - 2027. Logically, an increase in real GDPR growth rate should cause increased real GDPR. This effect was indeed observed (see Figure 46 in Appendix G).

The renewable energy goal gap was tested next. Under normal circumstances, a supply-demand gap type structure would be used. Due to the nature of the system, a true supply-demand gap is not present. Extreme condition tests included a 10 fold step increase in initial end user electricity demand and a renewable energy supply share goal that was set to 300% at the start of the modelling period. The results of each test variable on the renewable energy goal gap are presented in Appendix G (see Figure 48 and 49 respectively). The model performed as expected. A significant increase in the renewable energy goal gap can be observed when compared to the base case scenario.

Finally, Hessequa's total renewable energy power capacity was tested under extreme conditions. The renewable energy supply share goal was again set to 300% at the start of the modelling period.

Because RE funds are limited, the effects were not as obvious as other extreme conditions tests, but results were still as expected. RE capacity continued to grow, where it levelled off in the base case scenario. The effects of a ten-fold increase the initial rooftop PV capacity, capital cost of generation capacity and GDPR investment fraction were also tested. As expected, Hessequa reached its RE Goal faster in the cases where rooftop PV capacity and GDPR investment were increased. Compared to the base case, renewable energy generation capacity grew much slower when the capital cost of these technologies were increased. The results are presented in Appendix G (see Figures 50 to 52).

Table 13 presents a summary of the extreme condition test that were performed on the model.

Table 13: Extreme condition tests

Variable (Cause)	Step size	Variable (Effect)	Step start time	Step end time
Crude birth rate	x10	Population	2022	2027
Real GDPR growth rate	x10	Total End User Electricity Demand	2022	2027
Real Eskom electricity cost	x10		2022	2027
Initial End User Electricity Demand	x10	RE Generation Goal Gap	2017	2040
RE Generation GOAL	Set Goal to 300%		2017	2040
RE Generation GOAL	Set Goal to 300%	Hessequa total RE power capacity	2017	2040
Capital cost of generation capacity	x10		2017	2040
GDPR investment fraction	x10		2017	2040

4.4.4 Boundary adequacy testing

Boundary adequacy varies depending on the model's purpose. Many variables that are modelled as exogenous can be made endogenous by adding structural elements to the model. However, expanding the model in such a way will not always increase its usefulness (Sterman, 2000). It is therefore important to always keep the model's purpose in mind when questioning its boundary adequacy (Forrester & Senge, 1980).

The purpose of HessREM is to serve as a renewable energy planning tool for the Hessequa Municipality. To ensure boundary adequacy, the relevant stakeholders at the municipality were engaged and their inputs were taken into account. Study supervisors were also consulted to build confidence in the boundary adequacy. If requirements or the model's purpose change in the future, it can be developed further to accommodate the new requirements.

4.4.5 Dimensional consistency testing

This test evaluates the dimensional consistency of the model's rate equations and also whether the rate equations correspond to the real system (Forrester & Senge, 1980). The rate equations were evaluated on a continuous basis along with Vensim's built-in dimensional consistency tool throughout the modelling process.

4.4.6 Behaviour reproduction testing

Behaviour reproduction tests focus on reproducing historical behaviour (Forrester & Senge, 1980). No large scale renewable energy projects have been implemented in Hessequa. Thus, no behaviour reproduction tests can be performed regarding the effects of RE investment. Forrester and Senge (1980) also describes behaviour reproduction as a family of tests. Symptom-generation, a member of the behaviour reproduction test family, determines whether the model will recreate symptoms that motivated the models development in the first place. One such symptom was recreated, namely: The loss of municipal revenue due to increased uptake of embedded rooftop PV systems. Because of the small scale of the case study, data availability becomes a problem or limiting factor when attempting to reproduce historic behaviour in the model's output. As such, behaviour reproduction tests were not explicitly used in an attempt to recreate historic behaviour.

4.4.7 Behaviour anomaly testing

According to Forrester and Senge (1980), behaviour anomaly tests are used extensively during the model development phase. It is particularly useful for finding flaws in model assumptions. This test was indeed used frequently during model development to trace structural flaws. The test was also used in the model validation process. The following behaviour anomalies were introduced in the model and Hessequa's total renewable energy power capacity was used to study their impacts:

- Utility scale RET construction time for all technologies were set to 10 years.
- The lifespans for all utility scale RETs were set to 100 years.

The two anomalies were introduced individually as illustrated in Table 14. The behaviour anomaly test results were compared to the base case scenario that was also used in the extreme condition tests. The results were presented in Appendix G (see Figures 53 and 54).

Table 14: Behaviour anomaly test conditions

Test 1	RET Construction Time (years)			
	Solar PV	Wind Power	Biomass Power	Pumped Storage
Base Case	1	1	1	3
Behaviour Anomaly Test 1	10	10	10	10
Test 2	**RET Lifespans (years)**			
	Solar PV	**Wind Power**	**Biomass Power**	**Pumped Storage**
Base Case	25	25	30	40
Behaviour Anomaly Test 1	100	100	100	100

4.4.8 Sensitivity analysis

Sterman (2000) lists three sensitivity types, namely: numerical -, behaviour mode - and policy sensitivity. All models are numerically sensitive. This type of sensitivity occurs when the numerical values of results change due to changes in assumptions (changing the values of certain model parameters). Behaviour mode sensitivity is demonstrated when patterns of behaviour is changed in the model results due a change in assumptions. Policy sensitivity occurs when the desirability or impacts of a proposed policy become reversed as assumptions change.

When performing sensitivity analysis, Sterman (2000) recommends that a plausible range for parametric assumptions be determined first. The sensitivity analysis should then be performed over a much wider range. People are generally overconfident in their judgemental parameter estimates, even when parameters are statistically estimated. The reason for the latter is that sampling error is the only type of uncertainty taken into account when statistical methods are used for parameter confidence bounds estimation. Testing over a range that is up to twice as wide as suggested by judgemental or statistical methods is recommended as a simple rule of thumb.

Table 15 contains a summary of all the sensitivity analysis test performed on the model. It must also be noted that the sensitivity analysis tests were performed under the same base case scenario conditions as the extreme condition tests (as discussed in section 4.4.3). The sensitivity analysis results were presented in Appendix G (see Figures 55 to 70).

The four major variables that directly impact electricity demand, are demand elasticity of the electricity price, population, GDPR and GDPR per capita. Price elasticity values of up to -1.35 are encountered for the residential sector, and up to -1.745 for the mining sector in South Africa (Blignaut *et al.*, 2015). GDP elasticity of up to 1.2 is encountered in literature (Deloitte, 2012). GDPR per capita elasticity uses a proxy value based on income elasticity found in Ziramba (2008). The annual GDPR growth rate has varied significantly from 2004 to 2014 (0.6% - 10.4%) (Hessequa Municipality, 2017). Although the municipal area did not technically experience a recession in this time, it is highly plausible to occur given the current South African economic climate. This was taken into account in the sensitivity analysis. From local government's point of view, it will be useful to keep uncertainty in electricity demand in mind when planning for the future.

Only the capacity factors for biomass and pumped storage were subjected to sensitivity analysis due to the high uncertainty in these parameters. Literature only provides capacity factors for hydropower and does not seem to distinguish between the run-of-river type installations and pumped storage. The capacity factor ranges were based on global minimum and maximum values encountered in REN21 (2016). Due to more complete and accurate estimates made for wind and solar power, these technologies were not tested in the sensitivity analysis.

Because the capital cost of RETs are reported in US Dollar and often imported, the Rand – Dollar exchange rate will impact the possible annual generation capacity being installed. The exchange rate was therefore considered for sensitivity analysis. The exchange rate varied between 6.54 – 16.85 ZAR/USD for the period 2007 – 2017 (XE, 2017).

Owners of embedded generation capacity can install these systems to reduce their monthly electricity bill or to become completely independent from Eskom. Depending on their goal, the possible size of rooftop installations can vary significantly. Due to lack of reliable data on the current installation rates of rooftop PV systems and the average PV system size, base installation rate and the initial rooftop PV capacity were subjected to sensitivity analysis (see Table 15).

Table 15: Model sensitivity tests

VARIABLE (CAUSE)	UNIT	RANGE	VARIABLE (EFFECT)
ELECTRICITY DEMAND VARIABLES			
Demand Elasticity of Price	-	(-2) - 0	Total End User Electricity Demand
Demand Elasticity of Population	-	0 - 2	Total End User Electricity Demand
Demand Elasticity of GDPR	-	0 – 1.5	Total End User Electricity Demand
Demand Elasticity of GDPR per capita	-	0 - 1	Total End User Electricity Demand
RENEWABLE ENERGY CAPACITY VARIABLES			
Biomass power capacity factor	-	0.202 – 0.958	Biomass electricity generated
Pumped storage capacity factor	-	0.115 – 0.947	Pumped Storage electricity generated
ZAR US$ Exchange rate	ZAR/USD	4 - 25	Hessequa total RE power capacity
Average residential rooftop PV capacity	kW	1 – 8	Rooftop Solar PV capacity Rooftop PV Electricity Generated
Base PV installation rate	kW/year	20 - 180	Rooftop Solar PV capacity Rooftop PV Electricity Generated
Initial Rooftop PV	kW	50 - 1000	Rooftop Solar PV capacity Rooftop PV Electricity Generated
GDPR VARIABLES			
Real GDPR growth rate	%	(-4) - 12	Total End User Electricity Demand

4.5 Scenario Planning

Scenario planning is one of the final stages of the system dynamics modelling process, as described in Maani and Cavana, 2012). This part of the process deals with strategy and policy formulation. Maani and Cavana (2012) describe policy testing as changing a single internal variable, and strategy testing refers to testing a set of policies. Both of these refer to internal (controllable) changes in the model. They describe scenario modelling as the process where the planned strategies are tested under a range of external conditions.

Hessequa has no formal framework or strategy in place specifically for a renewable energy future. It is the author's hope that this work might serve as the first step towards developing such a strategy document and to help guide the planning and implementation of RET in the municipal area.

The main variables that are changed in the scenario simulations included the fraction of GDPR that will be invested in RET and the policy decisions for each technology's contribution to achieving Hessequa's renewable energy goal. Compensation for rooftop PV electricity fed back into the grid is also considered.

Five main scenarios are simulated in this work. They are as follows:

1) Business-as-usual Scenario - BAU
2) Low Investment Scenario (Biomass and Solar Power) – LIS (BS)
3) Low Investment Scenario (Solar and Wind Power) – LIS (SW)
4) High Investment Scenario (Biomass and Solar Power) – HIS (BS)
5) High Investment Scenario (Solar and Wind Power) – HIS (SW)

The following sub-sections will briefly discuss the conditions in each scenario.

4.5.1 Business-as-usual scenario

Under business-as-usual conditions, the only RET that is considered for investment is rooftop solar PV systems. This investment is assumed to emanate from private entities such as home owners and they receive no compensation for the electricity fed back into the grid. In this scenario, utility scale electricity generation plays no role in Hessequa's renewable energy future.

The business-as-usual scenario serves as a baseline. The other four scenarios are compared to these baseline simulation results to determine the impacts of expanding Hessequa's RET capacity.

4.5.2 Low investment scenarios

The energy summit and other green activities in the municipal area indicate that the people of Hessequa are, to some degree, aware of the need for renewable energy. In these scenarios Hessequa actively takes steps to reduce its dependence on Eskom electricity, reduce its carbon footprint and promote an overall greener future.

The renewable energy goal used in these scenarios can be read as follows: Hessequa aims to meet one third (33.3%) of its total end user electricity demand with locally generated renewable electricity. Usually such a goal will be accompanied by a specific deadline for when the goal should be achieved. Instead, the model can be used to illustrate progress towards a specified goal, given a certain investment and technology mix. The municipality can then use the model results to evaluate the likelihood of their renewable energy goal being reached. Once the goal is set, it should not be flexible and efforts must be made to achieve it within a certain timeframe.

In all four of the investment scenarios (LIS (BS), LIS (SW), HIS (BS), HIS (SW)) there is active investment into renewable electricity generation capacity. In the low investment scenarios a GDPR investment fraction of 1.5% is used. This indicates annual investment into renewable electricity generation capacity equal to 1.5% of the real regional gross domestic product. As explained in Section 4.2.15, investment will only occur when the renewable electricity generation is insufficient to meet Hessequa renewable energy goal.

For this part of the work only biomass, solar and wind power are considered as part of the scenario discussion. Policy decisions in LIS (BS) dictated that the renewable energy goal gap should be closed using REGGG Filled Fractions (see section 4.2.15 for an explanation of the term) of 70% for solar PV and 30% for biomass power. For LIS (SW), REGGG Fill Fractions of 60% solar PV and 40% wind power are used.

In the low investment scenarios, the municipality also compensates the owners of embedded generation capacity for feeding electricity back into the local grid. This feed-in-tariff is set at 50% of the real cost of rooftop PV electricity, as estimated in the model (see Section 4.2.8). It is estimated that 30% of all electricity generated by embedded generation systems would be fed into the local electricity grid.

It is further assumed that all electricity generated by RETs in Hessequa would be consumed in Hessequa. The assumption is also made that the municipality would be allowed to purchase electricity directly from IPPs and then resell it to customers. There are many legal and regulatory obstacles to such a scenario, but that might change in the future. The City of Cape Town wants to take the South African department of energy and the national energy regulator to court to challenge Eskom's exclusive right to procure electricity from power producers (Yellend, 2017). Should they be successful and granted the right to purchase electricity directly from IPPs, it will create a precedent and many other municipalities will likely want to do the same.

4.5.3 High investment scenarios

In the high investment scenarios the GDPR investment fraction is doubled to 3%. This allows Hessequa to achieve its renewable energy goal sooner, but presumably at a higher total investment. In this scenario the owners of embedded generation are compensated at 100% the real cost of rooftop PV electricity for all the electricity they feed back into the grid. All other assumptions used for the low investment scenarios apply to the high investment scenarios as well. A summary of the five scenarios are presented in Table 16.

Table 16: Main simulation scenarios

Scenario Number:	**1**	**2**	**3**	**4**	**5**
Model Variable	**Business as Usual**	**RET Investment Scenarios**			
		LIS (BS)	**LIS (SW)**	**HIS (BS)**	**HIS (SW)**
GDPR investment fraction	0.0%	1.5%	1.5%	3.0%	3.0%
RE Generation Goal	33.3%	33.3%	33.3%	33.3%	33.3%
Rooftop PV Compensation	No	Yes (50%)	Yes (50%)	Yes (100%)	Yes (100%)
REGGG Filled Fraction Solar PV	0.0%	70%	60%	70%	60%
REGGG Filled Fraction Wind Power	0.0%	0%	40%	0%	40%
REGGG Filled Fraction Biomass Power	0.0%	30%	0%	30%	0%
REGGG Filled Fraction Pumped Storage	0.0%	0%	0%	0%	0%

The simulation results of the scenarios listed in Table 16 are discussed in chapter 5. Alternative scenarios are also simulated with different technology mixes. These alternative scenarios are presented in Appendix H.

4.6 Conclusions

The aim of this chapter was to describe the dynamic model suggested by the second research sub-question and the corresponding research objective. Based on a qualitative CLD a quantitative system dynamics model was developed in order to address the third research sub-question, i.e. to determine an appropriate RE electricity mix for a given set of desired socio-economic and environmental outcomes. The SDM that was developed consists of a number of sub-models. Amongst the sub-models are the electricity demand sub-model, electricity supply sub-model, population sub-model, as well as a sub-model for each RET. The resulting SDM was tested and evaluated using a number of validation exercises. Thereafter the SDM was used to simulate different scenarios that would address the third research sub-question and the third research objective. The outcomes of these simulations are discussed in chapter 5.

CHAPTER 5: HESSREM SIMULATION RESULTS AND DISCUSSION

5.1 Introduction

The purpose of this chapter is to use the SDM that has been developed in the previous chapter as an aid in formulating policies that would contribute to the realisation of the desired socio-economic and environmental objectives through an appropriate RET electricity mix. In the following sub-sections the simulation results of the scenarios described in Chapter 4.5 are discussed.

Should the HessREM outcomes be implemented in reality, it will have varied impacts on a wide range of stakeholders. It is therefore important to consider the different stakeholder interests and potential impacts before presenting the model results to a particular stakeholder group. This challenge also creates an opportunity to view the model results from different perspectives. In the following discussion an attempt is made to address these different perspectives and highlight the most important aspects of the system and the simulation results.

Aside from minor embedded generation capacity and a 33 kW solar PV plant in Riversdale, Hessequa is dependent on Eskom to satisfy all of its electricity demands. Scenarios that were simulated investigated the impact of renewable energy technology investment within the municipal area. By expanding its renewable energy technology generation capacity, Hessequa hopes to improve access to a reliable electricity supply. At the same time the municipality hopes to improve its sustainability, both financially and environmentally. For these reasons environmental and socio-economic impacts of renewable energy technology investments are also investigated in the scenario simulations. Among others, these impacts include job creation, water demand and CO_2 emissions of RETs.

The simulation results can be considered as possible futures in the Hessequa electricity sector. The policies and assumptions in each scenario have a degree of uncertainty that should also be taken into account. It should be kept in mind that the SDM is a simplification of a very complex system that behaves in non-linear and unpredictable ways. Simulation of diverse scenarios provides a way to develop some understanding of the behaviour patterns of the modelled system.

This section discusses the main model variables under different scenarios. Historical data is also included in figures and discussions in cases where it was available and deemed relevant. Only the five main scenarios (BAU, two low investment scenarios and two high investment scenarios) are discussed in this section. The business-as-usual scenario (BAU) is intended to serve as a baseline for comparing the other two investment scenarios. For an overview of the alternative scenario simulations, see Appendix H.

5.2 Electricity Demand and its Drivers

To understand what is required to meet Hessequa's proposed renewable energy goal, one has to understand the future of electricity demand in the area. As stated in section 4.2.9, three main factors impact upon Hessequa's end user electricity demand profile, i.e. population size, GDPR and GDPR per capita. Each of these drivers of change are discussed in some more detail below.

5.2.1 Population size

Population data between 2001 and 2011 was obtained from census data (StatsSA, 2011). A population growth rate of 1.77% per annum was used to extrapolate population size to 2017 and the model was used to predict population statistics from 2017 to 2040. Population size was predicted to grow 41.4% from an estimated 58 642 people in 2017 to 82 709 people in 2040. This growth is illustrated in Figure 15.

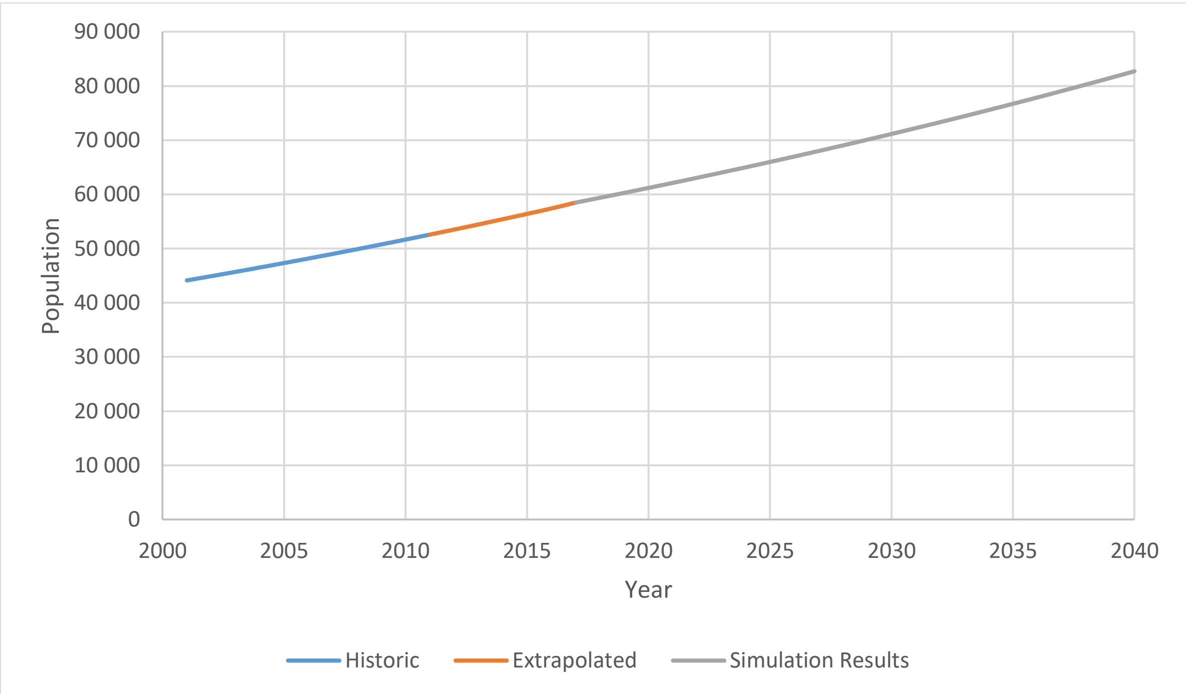

Figure 14: Hessequa's population from 2001 to 2040. Source: StatsSA (2011)

Given this large population increase, a significant increase in electricity demand can be expected. The larger population would require a significant increase in the delivery of other municipal services as well. However, the growing population does not necessarily mean that the municipality's income will increase proportionally. If most of the population increase is due to an increase in low income households, which will most probably be the case, the municipality might struggle to maintain free service delivery to these households at the current level. The other two drivers of change that are included in the SDM relate to economic output of the municipal region, expressed in terms of regional gross domestic product and regional gross domestic product per capita.

5.2.2 GDPR and GDPR per capita

Historic data (Hessequa Municipality, 2017) was used to determine Hessequa's real GDPR from 2005 to 2014. The 2.44% per annum real growth rate was used to extrapolate GDPR from 2014 to 2017 and the model was used to predict real GDPR from 2017 to 2040. Based on the average long term annual growth rate of 2.44%, Hessequa's real GDPR was predicted to grow from an estimated R 3.042 billion in 2017 to R 5.330 billion in 2040 (a 75.2% increase). Real GDPR is illustrated in Figure 16.

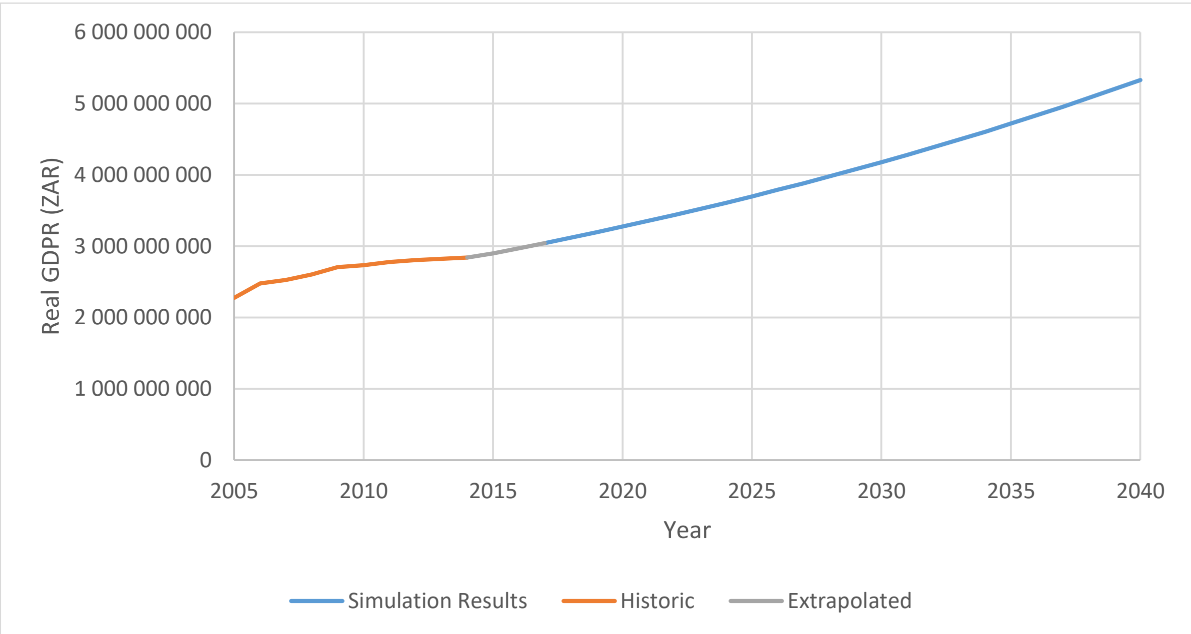

Figure 15: Hessequa's real GDPR from 2005 to 2040. Source: Hessequa Municipality (2014)

The economic growth predicted in the model is most likely an optimistic outlook. Between 2009 and 2014 (the latest available data), Hessequa's GDPR growth varied between 0.6% and 2% per year. Therefore, in reality, the estimated GDPR predicted by the model might be greatly overestimated. In reality, Hessequa's economy cannot be considered in isolation. It is influenced by economic conditions that impact all of South Africa. Therefore, any economic stagnation or recession experienced on a national scale will probably be reflected in the Hessequa economy was well, to a lesser or greater extent.

Real GDPR per capita is modelled as another driver of electricity demand. The historic estimates as well as the model predicted real GDPR per capita is presented in Figure 17. It was predicted to rise 23.9% from R 52 017 per capita to R 64 444 per capita between 2017 and 2040.

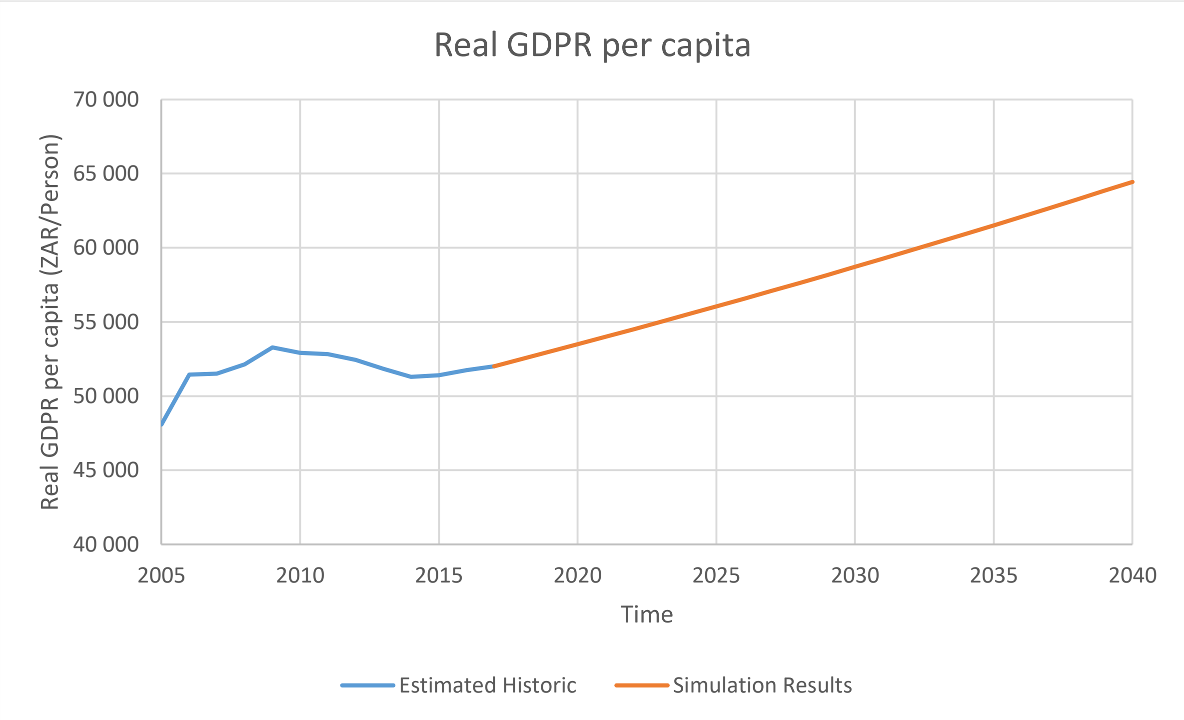

Figure 16: Real GDPR per capita from 2005 to 2040. Source: Hessequa Municipality (2014)

It should be noted that an increase in GDP per capita is not always a good indicator of a rise in standard of living. In some cases it could indicate only a rise in Gini-coefficient. Hessequa's 2014 Gini coefficient was reported as 0.54 (Western Cape Government, 2014). The significant increase in all three drivers of electricity demand indicate that electricity demand will also increase for the foreseeable future.

5.2.3 End user electricity demand

Hessequa's historic electricity demand was discussed in section 3.3. From the historical data, the area's electricity demand has remained relatively stagnant from 2010 to 2015. The Initial electricity demand in the municipal area was estimated to be 87 425 MWh for 2017. Total end user electricity demand increases by approximately 42.6% to 124 600 MWh in 2040 (see Table 17 and Figure 18).

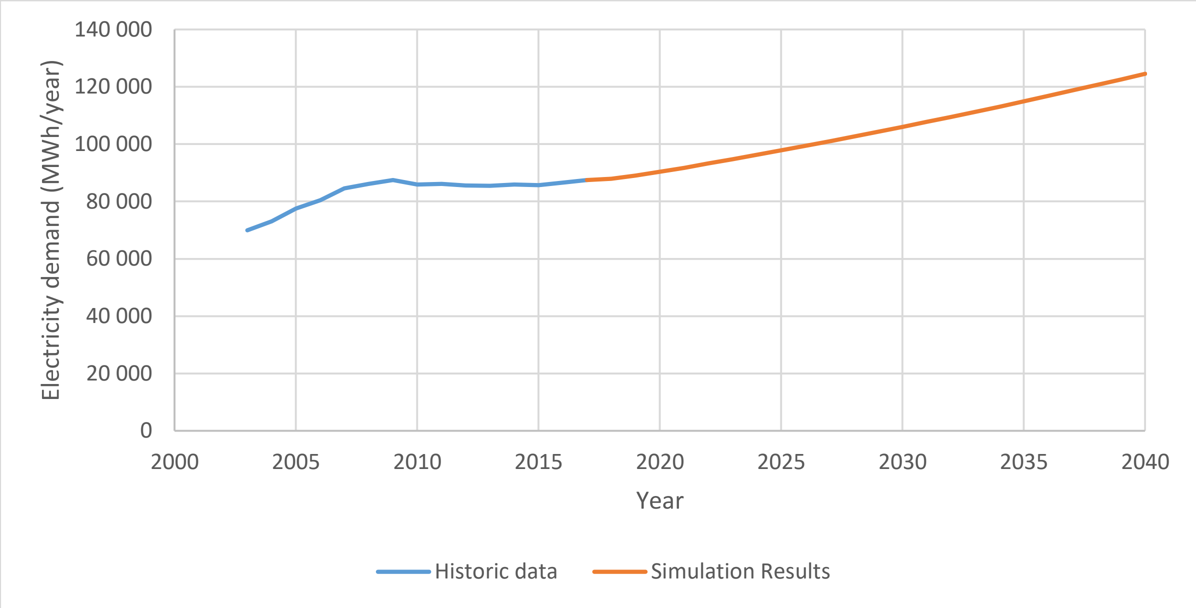

Figure 17: Hessequa's total end user electricity demand between 2003 and 2040. Source: Lesch (2017b)

The sectoral shares of total end user electricity demand only vary slightly between 2017 and 2040. The residential sector was responsible for 76.1 % of total end user electricity demand in 2017. This share increases to approximately 77.9% in 2040. The corresponding change in the business sector was from 20.7% in 2017 to 19.0% in 2040. Local government's share also decreased from 3.2% to 3.1% over this period.

The assumption was made that the municipality will continue to sell electricity at a tariff equal to the tariff it would have charged when buying electricity exclusively from Eskom (BAU). Therefore, local government is the only sector where electricity demand will vary from BAU when electricity is bought from an IPP instead of Eskom (assuming the IPP electricity price is lower than that of Eskom).

Table 17: Simulation results of end user electricity demand

Scenario	2017	2020	2025	2030	2035	2040
Total Annual Electricity Demand (MWh)						
All scenarios						
Business end user electricity demand	18 108	18 561	19 703	20 927	22 227	23 608
Residential end user electricity demand	66 525	68 914	75 050	81 793	89 141	97 150
Local government end user electricity demand	2 793	2 876	3 088	3 317	3 563	3 828
Total end user electricity demand	87 425	90 351	97 841	106 037	114 931	124 585

5.3 Electricity Sector Impacts

In the past, the vast majority of Hessequa's electricity was supplied by Eskom. Under business as usual conditions, Eskom will continue to be the only utility scale electricity provider to the municipal area. In the alternative scenarios, IPPs (which can be the local government or private entities) are encouraged to invest in RET and supply electricity directly to the municipality. The driving force behind this investment is Hessequa's renewable energy goal: to supply one third of end user electricity demand through renewable electricity generation in the longer term. In the model no time frame is set for reaching this goal. The amount of electricity that has to be generated locally to reach that goal continues to increase over time as total municipal electricity demand increases. Because of delays in the system model, goal overshoot can occur. When this happens, investment stops until the share of locally generated renewable electricity falls below the goal percentage again. The investment calculated in the model only accounts for utility scale RET projects, not for rooftop PV installations.

Table 18 contains the simulation results of the five main scenarios. It was assumed that no significant RET investment occurred before 2017. In the BAU scenario, there will be no investment in utility scale RETs until 2040. The low investment scenarios predict a total investment of R 679 million (BS) and R 813 million (SW) from 2017 to 2040 respectively.

Because of the higher GDPR investment fraction used in the high investment scenario, a larger investment is made earlier in the simulation. Two other factors lead to a significantly higher investment (R 838.3 million) being required in the high investment case scenario: goal overshoot and the fact that learning curve effects are better utilised in the low investment scenario simulations. Due to investments being made later, the capital cost of RETs are much lower and thus the total investment required in the low investment scenario is lower. This effect is especially visible since the learning curve effect of solar PV technology is larger than that of the other RETs.

Table 18: Simulation results for accumulated RET investment

Scenario	2017	2020	2025	2030	2035	2040
Accumulated RET Investment (R million)						
BAU	0	0	0	0	0	0
LIS (BS)	0	139	400	517	626	679
LIS (SW)	0	139	400	621	696	813
HIS (BS)	0	278	590	590	838	838
HIS (SW)	0	278	677	677	939	939

Simulation results regarding Hessequa's total RE generation capacity and electricity generation is presented Table 19. It should be noted that rooftop PV capacity and generation are included in the figures presented in Table 19. At the start of the simulation period, the only local generation capacity was assumed to be approximately 200 kW of private embedded generation capacity (rooftop PV), and a 33 kW solar PV installation owned by the local government. Under BAU conditions, the model predicted renewable electricity generation capacity to increase to 779 kW in 2040. According to Eskom's connection criteria and findings by Reinecke *et al.* (2013), an embedded generation capacity of 1 395 kW can be allowed in Riversdale (one of the major towns in Hessequa), given the town's current grid infrastructure. It can also be assumed that some of the towns will require infrastructure upgrades due to increased electricity demand. The model simulations would then imply that Hessequa's electricity infrastructure will most likely not be a limiting factor for embedded generation uptake under BAU scenario conditions. In all the active investment scenarios, generation capacity is significantly higher. In order to accommodate the higher generation capacities, local government will likely have to invest heavily in the electricity distribution network. However, this infrastructure investment was not a consideration in the model.

Table 19: Simulation results for Hessequa's total renewable energy power capacity and electricity generation

Scenario	2017	2020	2025	2030	2035	2040
Hessequa total RE power capacity (MW)						
BAU	0.23	0.28	0.39	0.52	0.65	0.78
LIS (BS)	0.23	2.09	11.14	18.77	16.48	20.95
LIS (SW)	0.23	2.34	12.32	23.56	21.78	27.38
HIS (BS)	0.23	3.90	20.35	18.50	19.23	24.16
HIS (SW)	0.23	4.40	24.23	23.99	26.57	28.60
Net electricity generation (MWh)						
BAU	300	358	488	636	790	943
LIS (BS)	300	4 347	24 350	41 295	36 181	46 108
LIS (SW)	300	3 784	20 413	39 151	36 081	45 386
HIS (BS)	300	8 335	44 795	40 662	42 233	53 202
HIS (SW)	300	7 210	40 302	39 802	44 034	47 356

Figure 19 and 20 illustrate the development of Hessequa's RET electricity generation capacity and the resulting electricity generation. Figure 20 also illustrates the RE electricity generation that would be required to meet Hessequa's RE goal as time progresses.

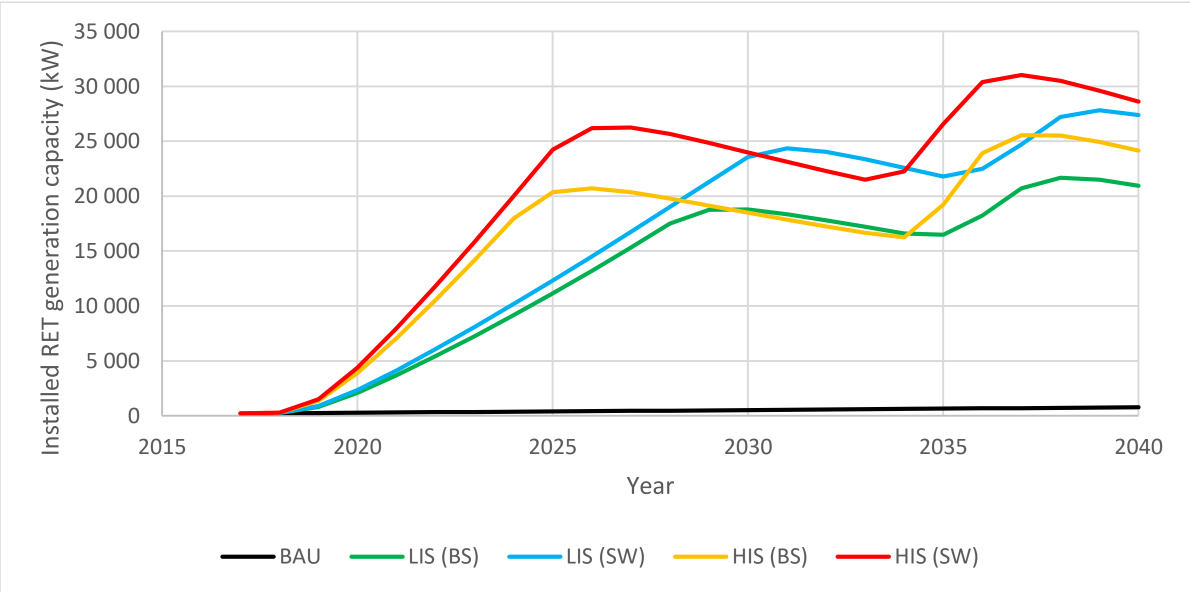

Figure 18: Simulation results for Hessequa's total renewable energy power capacity

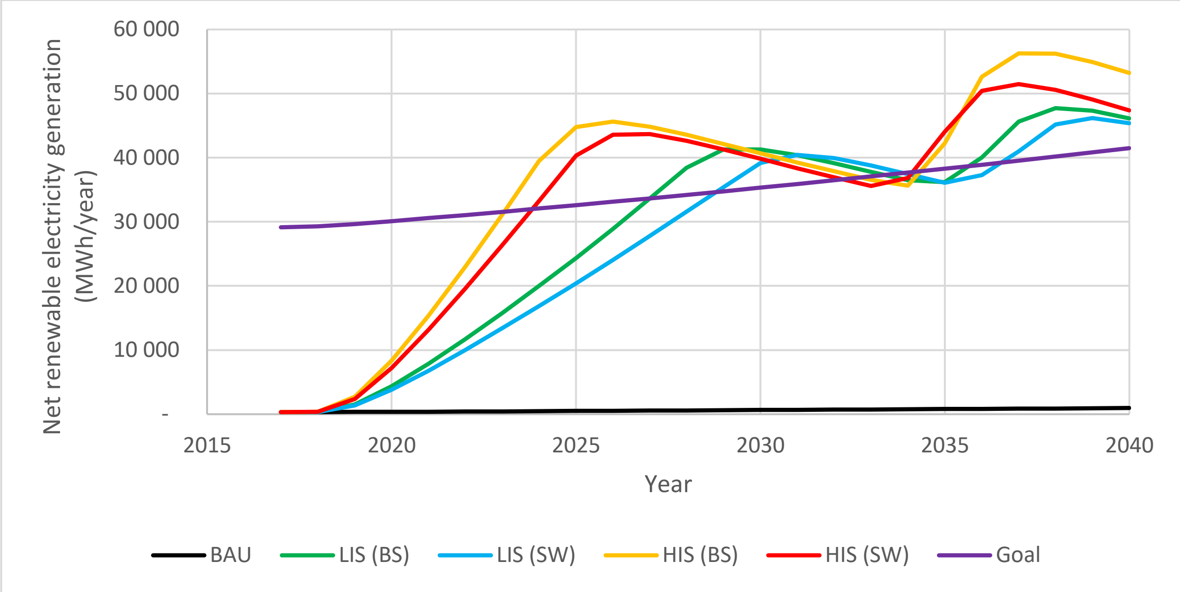

Figure 19: Simulation results for Hessequa's total renewable energy electricity generation

The portion of Hessequa's electricity demand that is supplied using RETs are presented in Table 20. As mentioned, system delays can cause goal overshoot and overinvestment, as demonstrated in the investment scenarios. In the low investment scenario, Hessequa's renewable energy goal can be achieved around the year 2027. As already stated, the goal and progress towards achieving it will change as electricity demand and the RET electricity supply change over time. Aggressive initial investment in both the low and high investment scenarios cause goal overshoot. In both cases the electricity demand increased and generation capacity becomes depreciated, leading to decreased electricity generation. As soon as the local share of electricity generation falls below RE goal levels, investment occurs and overshoots the goal again.

Table 20: Simulation results regarding the share of Hessequa's electricity demand being supplied by local RETs

Scenario	2017	2020	2025	2030	2035	2040
Share of Hessequa's electricity demand supplied by RET						
BAU	0.3%	0.4%	0.5%	0.6%	0.7%	0.8%
LIS (BS)	0.3%	4.8%	24.9%	38.9%	31.5%	37.0%
LIS (SW)	0.3%	4.2%	20.9%	36.9%	31.4%	36.4%
HIS (BS)	0.3%	9.2%	45.8%	38.3%	36.7%	42.7%
HIS (SW)	0.3%	8.0%	41.2%	37.5%	38.3%	38.0%

A 42.6% increase in electricity demand for Hessequa over the next two decades is almost insignificant on a national scale. Hessequa is however not the only place in South Africa where electricity demand is likely to increase. Depending on population growth and economic conditions, electricity demand for

South Africa as a whole may also increase dramatically over the modelling period. One of the model assumptions was that Eskom will always be able to supply the balance between local electricity production and total municipal demand. This assumption might not always hold, based on Eskom's historical performance regarding a reliable electricity supply.

5.4 Local Government Impacts

In most cases, local governments (municipalities) purchase their electricity directly from Eskom. The municipality adds a mark-up to the purchase price and then resells it for at a profit to local customers. For the majority of South African municipalities, electricity sales account for a large share of municipal revenues. Electricity sales can have a significant impact on the financial sustainability of these municipalities as profits from electricity sales are often used to cross-subsidise other functions of the municipality. Therefore, the purchase price of electricity and the profit margins involved will also impact the financial viability of a municipality. Table 21 and 22 contain the model simulation results for the average price of electricity when purchased by local government. Under BAU conditions, the purchase price of electricity is expected to increase by 53% between 2017 and 2040. In the RET investment scenarios, local government can purchase electricity at far lower rates. This will only be possible if the municipality is allowed to purchase electricity directly from an IPP, and if the IPP is able to offer electricity at the prices predicted in the model.

Table 21: Predicted real cost of Eskom electricity when purchased by local government

Scenario	2017	2020	2025	2030	2035	2040
Real Eskom Electricity Cost (R/kWh)						
All	0.81	0.86	0.94	1.03	1.13	1.25

Table 22: Simulation results regarding the real price of electricity when purchased by local government

Scenario	2017	2020	2025	2030	2035	2040
Real Hessequa electricity Cost (R/kWh)						
BAU	0.81	0.86	0.94	1.03	1.13	1.24
LIS (BS)	0.81	0.86	0.90	0.93	1.01	1.04
LIS (SW)	0.81	0.85	0.86	0.85	0.94	0.97
HIS (BS)	0.81	0.86	0.87	0.93	0.99	1.01
HIS (SW)	0.81	0.84	0.79	0.85	0.90	0.96

The predicted gross profit from electricity sales is presented in Table 23. For the BAU case, the model predicts gross profit on electricity sales to increase by 119.3% between 2017 and 2040. The increased gross profit is due to an increased electricity demand as well as an increased electricity sales tariff, given the assumed constant 46.09 % mark-up on purchase price thereof. In the low and high investment scenarios it was assumed that local government will be able to purchase electricity directly from IPP's. It was also assumed that the IPP electricity will be available at a lower cost than electricity supplied by Eskom. Based on these assumptions, the Hessequa local government's electricity sales gross profit in Rand per annum should increase between 195% and 226% between 2017 and 2040, depending on the investment scenario. The increased profits could potentially be used for improved socio-economic development, better service delivery, infrastructure improvements, etc.

Table 23: Simulation results regarding local government's electricity sales gross profit

Scenario	2017	2020	2025	2030	2035	2040
Electricity sales gross profit (R million)						
BAU	31.6	34.6	41.1	48.9	58.2	69.3
LIS (BS)	31.6	34.2	44.5	59.6	72.0	93.1
LIS (SW)	31.6	35.1	48.2	67.1	79.2	101.5
HIS (BS)	31.5	33.9	47.2	59.2	74.1	96.5
HIS (SW)	31.5	35.6	55.0	67.2	83.6	102.6

Assumptions had to be made regarding Hessequa's initial rooftop PV capacity as well as the rate at which new capacity was added. Table 24 and 25 present the simulation results of rooftop PV capacity as well as the financial impacts on local government that can be expected in each scenario. When owners of embedded generation capacity are paid a feed-in-tariff equal to 50% of the real cost of rooftop PV electricity (low investment scenarios), the added financial incentive causes a greater uptake of these systems. In the high investment scenarios, embedded generation uptake is even greater. As the embedded generation capacity increases, the municipality's electricity customer base shrinks. The estimated gross profit "lost" due to private electricity generation is captured in Table 25. Both the gross profit lost and the feed-in-tariff compensation would seem to negatively impact local government. However, the impact is relatively small when one considers the significant increase in electricity sales gross profit that can be expected between 2017 and 2040 (Table 25).

Table 24: Simulation results regarding rooftop PV capacity in Hessequa

Scenario	2017	2020	2025	2030	2035	2040
Rooftop PV capacity (kW)						
BAU	200	255	370	500	634	766
LIS (BS & SW)	200	287	451	623	790	940
HIS (BS & SW)	200	319	531	742	929	1 089

Table 25: Financial impacts of rooftop PV on local government

Scenario	2017	2020	2025	2030	2035	2040
Rooftop PV Compensation (R)						
BAU	0	0	0	0	0	0
LIS (BS)	16 988	19 910	24 081	28 532	33 471	36 573
LIS (SW)	16 988	19 910	24 081	28 532	33 471	36 573
HIS (BS)	67 952	88 608	113 516	135 910	157 566	169 510
HIS (SW)	67 952	88 608	113 516	135 910	157 566	169 510
Municipal electricity sales gross profit lost due to private PV generation (R)						
BAU	69 762	94 000	150 267	223 124	310 486	412 059
LIS (BS)	69 690	104 959	198 143	338 999	478 967	680 408
LIS (SW)	69 690	107 557	214 709	381 532	527 206	741 616
HIS (BS)	69 617	115 680	248 021	401 414	580 890	817 859
HIS (SW)	69 617	121 437	288 807	455 831	655 633	870 019
Total Financial Impact of Rooftop PV (R)						
BAU	69 762	94 000	150 267	223 124	310 486	412 059
LIS (BS)	86 678	124 869	222 224	367 531	512 438	716 981
LIS (SW)	86 678	127 467	238 790	410 064	560 677	778 189
HIS (BS)	137 570	204 288	361 536	537 325	738 457	987 369
HIS (SW)	137 570	210 045	402 322	591 742	813 200	1 039 529

5.5 Socio-Economic Impacts

RET investment should create job opportunities in the Hessequa area. Some of these jobs would be created during the construction phase of the projects and others during the operational phase. It was assumed that there is very little opportunity for localisation regarding construction, manufacturing and installation jobs. However, local people can be trained to perform operation and maintenance jobs on RET projects. Simulation results regarding the operation and maintenance jobs are captured in Table 26. Because of the relatively small generation capacity predicted in the model, the possible number of new job opportunities are also expected to be relatively low. For the scenarios where solar PV and wind power are used, the renewable energy industry in Hessequa is predicted to provide permanent jobs for 11 people. When biomass power and solar PV is used, it was predicted to create between 19 and 22 jobs.

Table 26: Local job opportunities created by RET investment

Scenario	2017	2020	2025	2030	2035	2040
Local job creation (Jobs)						
LIS (BS)						
Biomass Fuel Jobs	0	0	2	3	3	3
Biomass Power OM Jobs	0	1	5	8	7	9
Local Biomass power Jobs	0	1	6	11	10	12
Solar Power OM Jobs	0	1	4	6	5	7
Total Jobs	**0**	**2**	**10**	**17**	**15**	**19**
LIS (SW)						
Solar Power OM Jobs	0	0	3	5	5	6
Wind Power OM Jobs	0	0	2	4	4	5
Total Jobs	**0**	**1**	**5**	**9**	**8**	**11**
HIS (BS)						
Biomass Fuel Jobs	0	1	3	3	3	4
Biomass Power OM Jobs	0	2	9	8	8	10
Local Biomass power Jobs	0	2	12	11	11	14
Solar Power OM Jobs	0	1	7	6	6	8
Total Jobs	**0**	**3**	**19**	**17**	**18**	**22**
HIS (SW)						
Solar Power OM Jobs	0	1	5	5	6	6
Wind Power OM Jobs	0	1	4	4	5	5
Total Jobs	**0**	**2**	**9**	**9**	**10**	**11**

However, biomass fuel harvesting jobs could be greatly underestimated in the model. In most cases, fuel harvesting is likely to have a high degree of mechanisation. If the local government for instance requires an IPP to limit mechanisation in biomass harvesting, it could increase the number of jobs created. However, doing so will most likely also have a negative impact on the operating cost of an IPP producing biomass electricity. The result will be a higher electricity cost. The trade-off will have to be investigated in detail before a decision is made.

5.6 Environmental Impacts

The two main environmental impacts considered in the model are water requirements and carbon dioxide emissions of RETs. Both of these factors are also important from a sustainability point of view. In a water scarce country like South Africa it is important to preserve water resources. Coal-fired electricity generation requires a vast amount of water. Eskom reported a water usage of 314 billion litres for 2016 (Eskom, 2016a). Unlike coal-fired power, RETs like solar PV power require no water during operation. However, the panels do need to be cleaned to maintain their efficiency. Biomass power generation utilises many of the same principles as coal-fired power generation. As a result, water consumption for biomass electricity generation is much higher than for solar PV technology (3.7 times higher in the model assumptions). The simulation results regarding RET water requirements are presented in Table 27. Even though biomass electricity accounts for only about 30% of total RET electricity generation (in the scenarios where biomass electricity is considered), it would be responsible for over 60% of water consumption for the majority of the simulation period. For the scenarios where only solar and wind power are used, water consumption is expected to be significantly lower than for scenarios that include biomass.

Table 27: RET water requirements

Scenario	2017	2020	2025	2030	2035	2040
Total RE water consumption (m3/year)						
BAU	102	122	166	216	269	321
LIS (BS)	102	2 583	14 993	25 620	22 579	28 861
LIS (SW)	102	830	4 274	8 155	7 550	9 488
HIS (BS)	102	5 045	27 705	25 308	26 375	33 337
HIS (SW)	102	1 538	8 376	8 307	9 207	9 916

Technology with a high specific water consumption rate may not be desirable in a water scarce area. Hessequa's water balance for 2009 indicated "revenue-water" of 2 315 741 m^3 and "non-revenue water" of 414 259 m^3 (Hessequa Municipality, 2017). Non-revenue water is the water that is processed, but is lost. In the HIS (BS) case presented in Table 27, RETs will require 33 337 $m^3/year$. This is equal to 8.05% of 2009's non-revenue water losses. If local government can improve or maintain water infrastructure, RET water requirements should not be considered a major obstacle to their implementation.

Since biomass electricity generation is expected to be fuelled by invasive alien plants, the argument could be made that high water requirements for a biomass plant can be justified. IAPs would have consumed a significant amount of water if they had not been harvested. A biomass power plant may therefore offset a portion of its water requirements due to IAPs being used for fuel. The estimated annual biomass fuel requirements are captured in Table 28.

Table 28: Fuel demand of biomass electricity generation

Scenario	2017	2020	2025	2030	2035	2040
Biomass fuel demand (t/year)						
BAU	-	-	-	-	-	-
LIS (BS)	-	1 417	8 606	14 841	13 173	16 898
LIS (SW)	-	-	-	-	-	-
HIS (BS)	-	2 833	15 988	14 717	15 400	19 543
HIS (SW)	-	-	-	-	-	-

One of the main environmental benefits of most RETs is the fact that they produce no direct carbon dioxide emissions during operation. However, the model does account for life cycle CO_2 emissions of RET. Table 29 contains the predicted CO_2 emission for the Hessequa area between 2017 and 2040. Figure 21 also includes the historic estimated CO_2 emissions. Under BAU conditions, emissions were predicted to increase by 37% between 2017 and 2040. It should again be noted that these emissions are a result of electricity consumed in the Hessequa area. The physical emissions are produced at power plants in other parts of the country where most of the electricity used in Hessequa is generated. Therefore, the impact of increased emissions (under BAU conditions) will not be experienced within the Hessequa area. Following the implementation of RET for electricity generation, annual CO_2 emissions are predicted to decrease significantly from business-as-usual. The predicted emission reductions will vary, depending on the share of Hessequa's electricity generated through RETs. Figure 21 presents historic emissions as well as the model predicted CO_2 emissions for each scenario.

Table 29: Hessequa's electricity related carbon footprint

Scenario	2017	2020	2025	2030	2035	2040
Annual CO2 emissions (t/year)						
BAU	87 598	90 064	96 682	103 862	111 597	119 934
LIS (BS)	87 598	86 525	75 720	68 498	81 134	81 425
LIS (SW)	87 609	86 776	77 656	67 377	78 454	78 538
HIS (BS)	87 598	82 986	57 764	69 067	75 915	75 375
HIS (SW)	87 609	83 475	58 645	66 764	70 973	76 705
CO2 emission reduction						
BAU	0%	0%	0%	0%	0%	0%
LIS (BS)	0%	4%	22%	34%	27%	32%
LIS (SW)	0%	4%	20%	35%	30%	35%
HIS (BS)	0%	8%	40%	34%	32%	37%
HIS (SW)	0%	7%	39%	36%	36%	36%

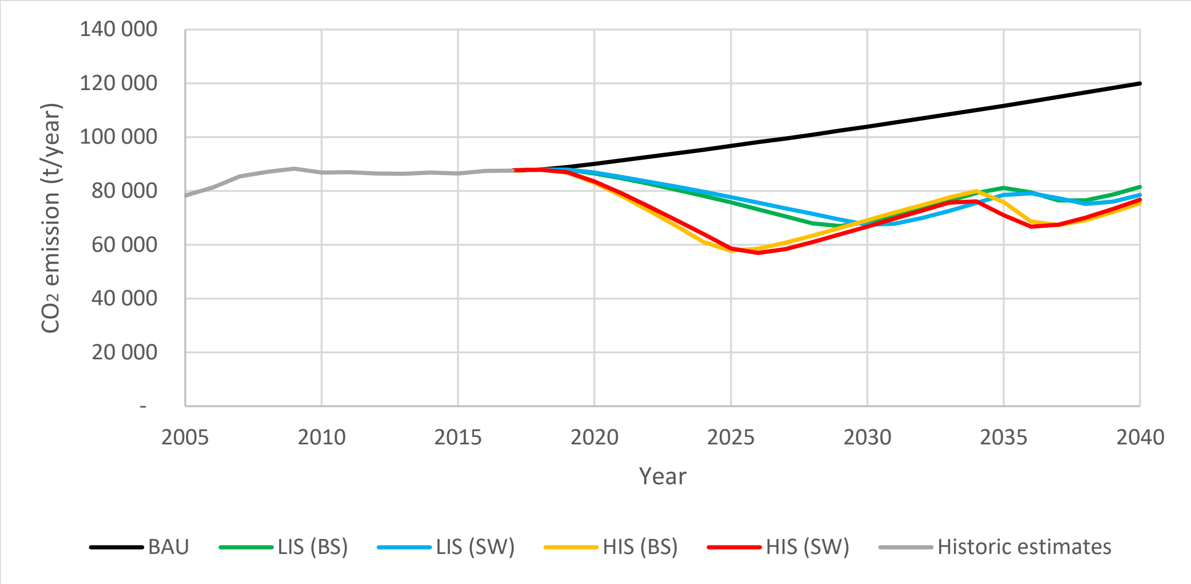

Figure 20: Hessequa's annual CO2 emissions

According to the World Bank (2013b), South Africa's 2013 total man-made CO_2 emissions were 471 238 836 t. Hessequa's total electricity emission for the same year were estimated around 86 341 t, less than 0.02% of South Africa's total CO_2 emissions. Never the less, it is important to consider reduced emissions in the South African context, rather than a local context. When RET is implemented anywhere in South Africa, it contributes towards the entire country's efforts in the fight against global warming and pollution. Since South Africa's electricity sector is extremely carbon intensive, it offers a great opportunity for reducing the country's carbon footprint. If Hessequa can serve as testing ground for the implementation of RETs that serve the immediate area, it could potentially lead other municipalities doing the same. Only then will an impact be visible on a national level.

5.7 Model Limitations

Like all models, the HessREM has limitations. Many of these are linked to resource or time constraints in the model's development, modelling difficulty or access to data. This sections will briefly discuss some of HessREM's limitations.

The model does not take economies of scale into account. RET generation capacity required in the model scenarios is relatively small compared to REIPPPP projects. There is a good chance that these small local projects will not be able to draw much benefit from economies of scale. As a result, both the capital cost of RET and the cost of electricity predicted by the model could be underestimated.

As already stated, no concrete data regarding the installed embedded generation capacity in Hessequa was available at the time of writing. Once regulations are finalised and the municipality is ordered to create a database of embedded generation capacity, more accurate data can be used in the model. The results of over- or underestimating the current installation rate, installed capacity or market potential of embedded generation can have a significant impact on local government's electricity sales.

The model itself does not evolve as real world conditions (economic, technological, political, social etc.) on which it was built change. To ensure the model remains useful for future use, it will require continuous updates and adjustment as certain parameters change.

Finally, in this work Hessequa was used as a case study. Although the system dynamics model includes factors that are relevant to most municipalities, the model results and recommendations cannot be generalised. In order to use the model for other municipalities, parameter values and in some cases the model structure would need to be adjusted.

5.8 HessREM Results and Discussion Summary

Research sub-question three is about the policy options that would contribute to a RET mix that would correspond to various sets of pre-defined and desired socio-economic and environmental outcomes. This chapter discussed HessREM results for a business-as-usual, as well as four RET investment scenarios. The drivers of electricity demand remains relatively constant regardless of the scenario under investigation. Impacts of renewable energy technology investment on the electricity sector and local government were presented. Socio-economic impacts in the form of job creation were presented and water requirements, biomass harvesting and CO_2 emissions were considered under environmental impacts.

In most cases the impacts of scenarios that include solar PV and biomass power were more beneficial than business-as-usual or solar PV and wind power investment scenarios. More jobs were created, more electricity was generated, municipal gross profits were higher and emissions were reduced more. Because of the higher RET generation capacity, water requirements were higher in the scenarios that included biomass power. It was noted that, due to high investment occurring earlier in the high investment scenarios, the full benefit of learning effects could not be realised. As a result, the two high investment scenarios required more investment to achieve the same goal as the low investment scenarios.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Renewable energy is steadily starting to replace carbon-based fossil fuels across the globe as the preferred source of energy. South Africa once seemed to follow this trend. Eskom, the national electricity utility company and state owned enterprise has a monopoly in the electricity sector. Eskom has refused to sign PPA's with many of the winners in the latest REIPPPP bid windows and these actions have limited the growth of the renewable energy electricity sector in the country. The electricity sector is tightly regulated by NERSA and regulations regarding electricity generation and trade are often ambiguous. Steep electricity tariff hikes have led to many electricity consumers to invest in embedded generation technologies and are becoming independent from the national grid. The impacts of increased embedded generation have a direct and negative impact on the financial income statements of many local government municipalities, who depend on profits from electricity sales to subsidise other municipal services.

The local government of Hessequa Municipality decided to take a pro-active approach to investigate the impacts of renewable energy technology investment in the area on electricity revenues as well as on private embedded generation, the environment and job creation. Research objectives for this study included the following:

- To review the current technologies that could be considered for supplying renewable electric energy to the Hessequa Municipality.
- To develop a model to determine an appropriate and sustainable electric energy mix for the Hessequa Municipality.
- To find policy options that would contribute to the most appropriate renewable electric energy supply mix in terms of different sets of desired outcomes for the economy, society and environment of the municipal area.

For the first objective, various renewable energy technologies were reviewed. Solar PV, wind power, biomass power and pumped storage were considered to be technically and practically viable for the area. This initial analysis was based on criteria related to capital cost, levelised cost of electricity generated, resource availability, technology maturity and other technical constraints.

If Hessequa's local government is allowed to purchase electricity from an IPP at a lower cost than from Eskom, it might significantly increase the municipal profits from electricity sales.

To address the second and third research objectives a quantitative model had to be developed. Thus the Hessequa Renewable Energy Model (a system dynamics model) was developed as an aid or tool to help local government to determine an appropriate electricity supply mix for the municipality. The model was used also to test various policies that may impact upon the local electricity system. Thus the development and testing of the system dynamics model addressed the second research objective. Next a number of policy options were developed and evaluated with the SDM in order to address the third research objective. Modelling of the policy options presented valuable insights for policy makers.

HessREM was used to investigate a variety of RET investments and policies through simulations. A business-as-usual scenario was created to serve as a baseline. Four other scenarios were simulated that focused on RET investment. Based on simulation results, it was recommended that Hessequa Municipality should encourage investment in an electricity supply mix with a large share of solar PV and biomass power. This technology mix will achieve Hessequa Municipality's renewable energy goal at a relatively low cost, compared to electricity supply mixes that contain wind power. The solar PV and biomass power scenarios also predicted some of the lowest electricity costs, greatest job creation potential and an additional environmental benefit of invasive alien plant clearing.

The four investment scenarios also investigated the impacts of incentivising the installation of embedded generation through a feed-in-tariff. Based on model assumptions and the simulation results, embedded generation capacity does not pose a significant threat to municipal electricity profits. In all investment scenarios investigated, local government can be encouraged to incentivise the installation of embedded generation in order to diversify the Hessequa electricity supply mix.

Currently, strict electricity regulations and politics are considered to be the biggest obstacles in RET implementation in Hessequa.

The system being investigated in this work was a complex system and it should be managed as such. Unintended consequences are a trade mark of complex systems. Any policy options should therefore be considered with great care before being implemented. The SDM developed for this study may be employed to model different policy scenarios and the expected outcomes thereof.

6.2 Recommendations Based on Simulation Results

System dynamic models are valuable tools for system level analysis of complex systems. They can be used in a wide variety of situations, especially when decisions need to be made regarding the management of a system. Hessequa Municipality is by no means a closed system, meaning that there are many external factors that can influence conditions within the municipal area. However, the factors that relate to local government's electricity revenue, the increase in embedded generation as well as other socio-economic and environmental factors should be managed in a manner that is sustainable and promotes development.

Hessequa's electricity sector is indeed a complex system and should be managed as such. HessREM aims to provide insight into the factors that impact upon Hessequa's electricity sector as well as the impacts of the electricity sector on the environment, society and local government. Policy options can be explored in the model and the results can be used to inform decision making processes within the municipality.

Model simulations suggested that the most appropriate electricity supply mix for the Hessequa Municipality will likely be a combination of solar PV, biomass power and Eskom supplied electricity. Local government should thus encourage investment in those two RETs. This will ensure that Hessequa's electricity supply is diversified. Investment in wind power RET is not recommended because of the low capacity factor and relatively high capital cost thereof.

Initially, there were concerns that increased rooftop PV embedded generation may pose a threat to local government's electricity sales and related profits. Based on the simulation results, embedded generation will not have a major impact on the municipality's financial sustainability. On the contrary, the installation of private rooftop PV systems can be encouraged by local government, under the right conditions. The amount of money being saved by purchasing electricity directly from an IPP will be more than sufficient to pay a feed-in-tariff to those who supply surplus electricity to the local grid. Encouraging the installation of embedded generation capacity also portrays local government as a "Green Champion", actively pursuing a more environmentally sustainable future.

Although there is a level of uncertainty regarding the price of electricity purchased from an IPP, it was modelled to be cheaper than Eskom's electricity price. If local government can indeed negotiate with NERSA, national government and Eskom for the right to purchase electricity directly from an IPP, it is recommended that local government resell the electricity as if it was purchased from Eskom. In other words, when electricity is sold to end user customers, it should not be offered at a lower rate than BAU. The added profits can be used for infrastructure improvements, economic development initiatives like tourism and local skills development.

Although solar PV technology is predicted to be significantly cheaper in terms of capital cost and the cost of electricity when sold to local government, biomass power should not be discarded. The environmental considerations and job creation potential involved in biomass power generation make a compelling argument for its share in the local electricity supply. If invasive alien plants are used as fuel in biomass power plants, areas with high IAP concentrations can be cleared. If enough invasive plants are cleared, there should be a marked impact on water supply in the area. Biomass harvesting is a low skill job. Very little, if any, training is needed before harvesting positions can be filled. Although the impact on local unemployment will be limited, it will not be negligible.

It is extremely unlikely that renewable electricity production anywhere in Hessequa will exceed demand at any given moment. That means there will be no electricity produced locally that is not immediately consumed locally. It also makes no sense to buy electricity from Eskom and then store that electricity for later use. Building electricity storage facilities like a pumped storage dam is therefore not recommended. Due to the low capacity factors predicted for wind power in the area, it is also not recommended to invest in wind power generation capacity. Appendix H does offer simulations where both pumped storage and wind power are included as part of Hessequa's electricity supply mix, but in all scenarios the predicted results were inferior to solar PV and biomass power investment options.

6.3 Recommendations for Future Work

After having completed the model development phase, and with the benefit of hindsight, many opportunities were identified for improving the model and its usefulness. Some of these opportunities and the recommended improvements in future work are discussed in this section.

6.3.1 Impacts on the economy

Although the impact of expanding renewable electricity generation capacity on the environment, society and the economy is expected to be positive, all benefits have not been included in the model simulations. Investigating the possible economic impacts of expanding Hessequa's RET generation capacity might be insightful. It was assumed that all construction, manufacturing and installation of RET would be conducted by non-local people, due to the specialised skills required. However, local business opportunities might be available in manufacturing steel frames for mounting solar PV panels or other components required for RETs. This and other impacts of RET investment on GDPR can be investigated and included in the model.

The model will benefit from a more thorough review of economic literature on electricity modelling. One example is the improvement of elasticity estimates. The model assumed that elasticities will remain constant throughout the modelling period. This is a simplification. As reported by De Wit, Heun and Crookes (2013), the elasticity of energy goods are a function of the income of consumers demanding the good, price of the energy good, demand of the energy good, the energy good's supply, the production inputs of the good and price of substitutes and complements of the energy good. The inclusion of these parameters in the model will greatly improve the accuracy of future electricity demand estimates.

It is further recommended that a more detailed approach is followed when modelling GDPR for a more accurate estimation of economic activity in the municipal area. In this work GDPR was approximated as a stock, while in reality it functions more like a flow.

6.3.2 Improved resource analysis

Many assumptions were made regarding the availability of IAP biomass (see Appendix E). A more detailed study should be conducted to determine how appropriate electricity generation from invasive biomass is. Areas with the highest density of biomass as well as relatively easy access need to be identified. Estimates can then be made on possible annual biomass harvesting, transportation and labour costs, etc. This will make it possible to predict the cost of biomass electricity more accurately, and also the feasibility thereof.

An analysis of pumped storage potential for the Koerentepoort dam near Riversdale is also advised. This will improve the accuracy of electricity generation estimates and provide an indication of energy storage potential for Hessequa.

A more complete resource availability analysis and a financial viability analysis should always be done before any investment decision is made. This system dynamics model was designed as a planning tool, but it is not sufficient to be used in isolation.

6.3.3 Infrastructure investment

It is highly unlikely that Hessequa's current electricity infrastructure will be able to support the 42.5% increase in electricity demand between 2017 and 2040, even under business-as-usual conditions. When the RET generation capacity is added to the grid, it is highly likely that major infrastructure upgrades would be required. Incorporating electricity infrastructure in the model would create a more accurate representation of reality. It would also enable the modeller to make more accurate estimates regarding the total investment that would be required to meet local government's renewable energy goals. Such an expansion in the model would also require a disaggregate approach to electricity demand and supply. Each town's electricity demand will have to be calculated individually, as well as the factors that drive the demand.

6.3.4 Seasonal changes in electricity demand

The model does not capture daily or seasonal changes in electricity demand or supply. A significant increase in electricity demand can be observed in Hessequa during the summer holiday season. The increase is largely due to some of the coastal towns being popular holiday destinations. Solar PV can produce more electricity during the hot and sunny summer months. Installing enough solar PV capacity can reduce Hessequa's peak annual demand which occurs during the summer months. Local government might then be able to negotiate better electricity prices when purchasing electricity from Eskom. Although it might be possible to model these effects using system dynamics models, another modelling method is probably more suitable.

6.3.5 Alternative goals

The renewable energy goal used in the model influences many of the model's outcomes. Different goal formulations should be considered to investigate alternative scenarios. Examples may include the following:

- Meeting all electricity demand growth in Hessequa through renewable electricity generation.

- Aim to meet 50% or 100% of Hessequa's electricity demand with renewable electricity before 2040.
- The goals can also have more of an environmental focus that aim to reduce CO_2 emissions, instead of placing the main focus on renewable electricity generation.

Changing local government's goals related to RET might require changes to the model structure, but these scenarios are worth investigating to determine how much investment would be required and how realistic or achievable the goal is in each case.

6.3.6 Investment sources

Although the model investigates the impact of RET investment in the Hessequa area, the sources of these investments are not included in the model. As mentioned in section 4.2.15, various institutions can provide funding for these projects, but the conditions under which the funds are made available will differ. The impacts of different financing options can be investigated in an improved version of HessREM.

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Appendix A: The State of Renewable Energy

A 1.1 The global state of renewable energy

In 2011 the UN's Sustainable Energy for All (SE4All) sets three energy related goals for businesses, governments and civil society around the world to achieve by 2030. These goals are: (1) Universal access to electricity as well as clean cooking fuels, (2) to double the share of energy supplied from renewable resources, and (3) to double the rate at with energy efficiency is improving (World Bank, 2014). A total of 102 countries have joined the SE4All initiative and 83 of these are developing economies. By 2014 a total of 144 countries had set renewable energy targets (REN21, 2015). Of these, 138 countries across the globe have support policies for renewable energy. The most common instruments are feed-in tariffs and RE tenders. Distributed generation, net metering, and biofuel blend policies or incentives are also being implemented. Most countries that have these policies also set RE targets. All 144 countries currently have RE targets, but most of these targets are not binding (World Bank, 2015). Currently, renewables and especially power generation are expected to grow in the medium term and to level off around 2020 (IEA, 2014)

In 2010 renewable energy contributed 17.8% of the total global final energy consumption (TFEC) and it increased to 18.1% by 2012. The increased share of RE was due to accelerated growth in RE and a decrease in the growth of TFEC. If the current trends continue RE will likely contribute approximately 19.4% of TFEC by 2030 (World Bank, 2013a). However, SE4All set a RE target of 36% of TFEC by 2030. According to two scenarios (New Policy Scenario and the 450 Scenario) this target will be very challenging to reach. Each of these two scenarios predicts a RE share of the TFEC of 24% and 29.4% respectively for 2030 (World Bank, 2015). Fundamental change is required for RE production and consumption in order to reach the SE4All RE targets. It was estimated that the annual investment required to meet the SE4All renewable energy goal for 2030 is $650 billion (World Bank, 2015).

Even though globally access to electricity has increased, Sub-Saharan Africa (SSA) and South Asia still require great efforts regarding access to energy, with electrification rates of 32% and 74% respectively in 2010 (World Bank, 2013a). Much potential exists for renewable energy in regions with low electrification and developing economies. If energy is supplied using RE technology from the start, lessons can be learned from more advanced countries, thus avoiding mistakes and unsustainable fossil fuel based solutions can be leapfrogged (Bhattacharyya, 2010).

From 2010 to 2012 half of the new electricity generating capacity was from renewable energy and the growth rate of renewable electricity was double that of electricity generated from fossil fuels. This can largely be contributed to decreasing costs of renewable energy technologies. International renewable electricity generation capacity grew from 1210 GW in 2010 to 1440 GW in 2012 (World Bank, 2015) to 1849 GW at the end of 2015 (REN21, 2016). Installed RET electricity capacities are reported in Table 30.

Table 30: State of global renewable energy – Installed capacities. Source: REN21 (2015, 2016)

Technology	Units	2004	2012	2013	2014	2015
Hydropower	GW	715	960	1000	1055	1064
Geothermal power	GW	8.9	11.5	12	12.8	13.2
Solar PV	GW	2.6	100	139	177	227
Concentrated solar power	GW	0.4	2.5	3.4	4.4	4.8
Biomass power	GW	36	83	88	93	106
Wind power	GW	48	283	318	370	433
Total RE power capacity	**GW**	**810.9**	**1440**	**1560.4**	**1712.2**	**1849**
New annual RE power and fuels investment	Billion US$	39.5	249.5	214.4	-	285.9
Countries with policy targets		48	138	144	-	173

By 2010, generation capacity for renewable electricity was approximately 1259 GW and 4160 TWh was generated during that year. The 2010 shares of fossil fuels, nuclear and renewable energy are indicated in Figure 22 and a further breakdown of the renewable energy sources is presented in Figure 23.

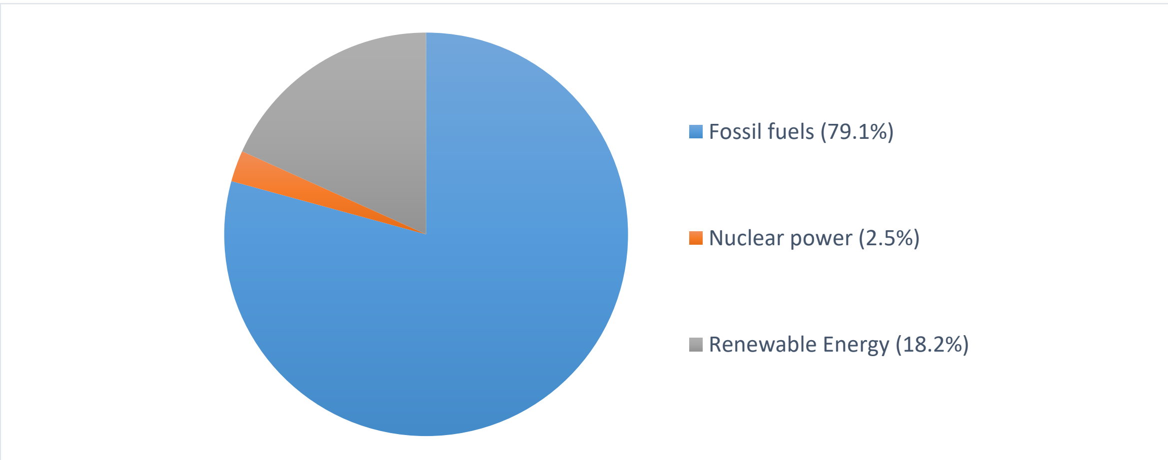

Figure 21: Energy sources contributing to global TFEC. Source: World Bank (2013a)

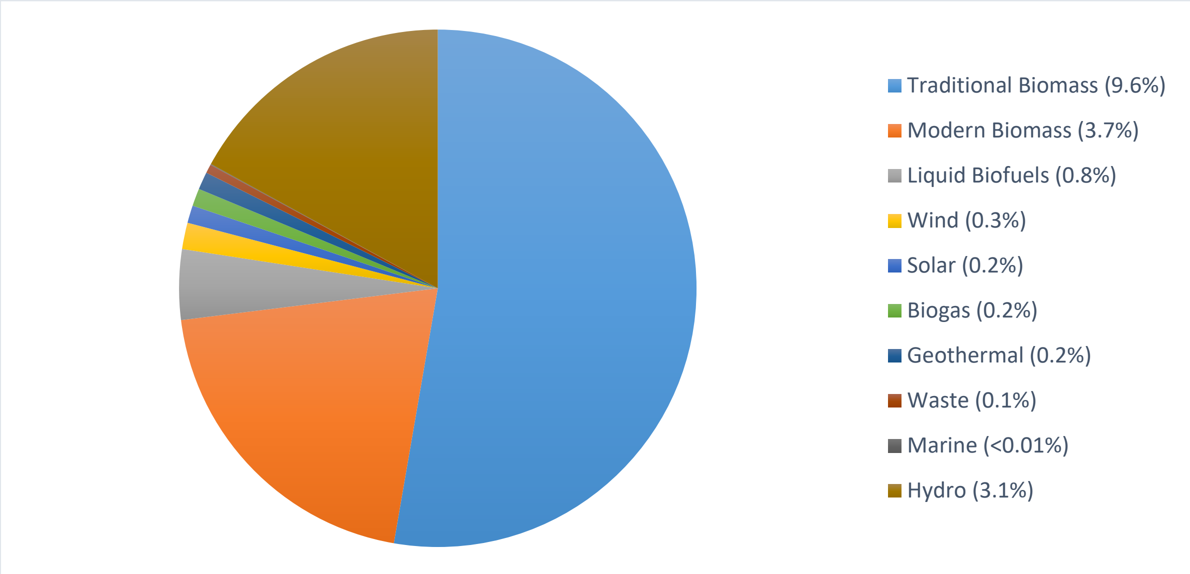

Figure 22: Renewable energy sources as portion of global TFEC. Source: World Bank (2013a)

Various factors have contributed to the rapid growth of RE over the last two decades. In particular, technology cost reduction and sustainability policies have had large impacts on investments in RE. Figure 24 presents the compound annual growth rate (CAGR) of each renewable energy source between 1990 and 2010.

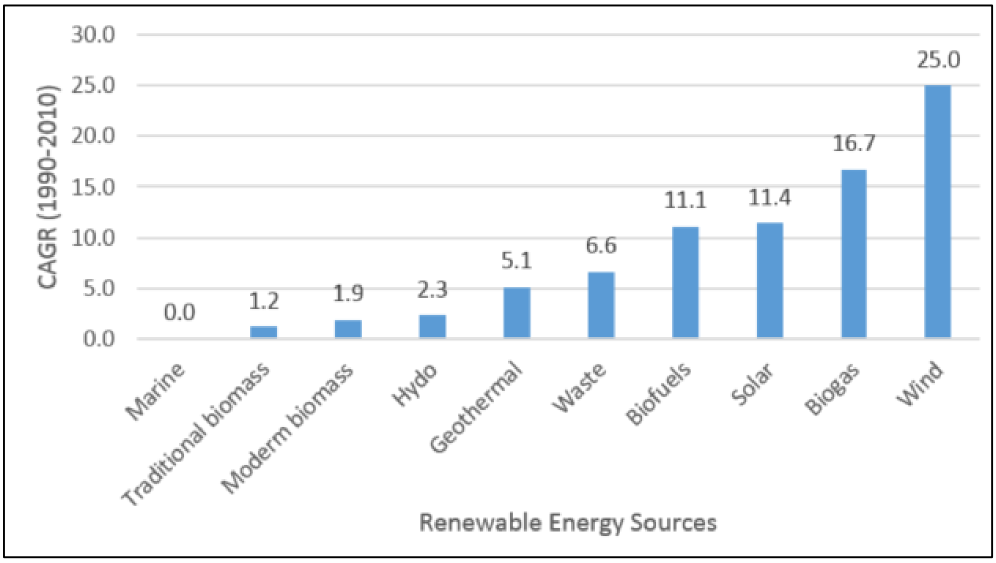

Figure 23: CAGR of renewable energy total final energy consumption. Source: World Bank (2013a)

Considering electricity production, the share of electricity generated from renewables decrease from 1990 (19.5%) to 2003 (17.5%) due to an electricity demand growth greater than the growth in renewable electricity generation. In 2010 the RE share of electricity increased again to 19.5% (World

Bank, 2013a). Hydropower and wind power was respectively responsible for 83% and 8% of the electricity generated using renewables (World Bank, 2013a).

During the 2005 - 2010 period, renewable energy electricity grew at an average compound annual growth rate (CAGR) of 4.9% to 4 302 TWh in 2010. At the end of 2012 the market grew to 4 829 TWh (approximately 6% per year) (World Bank, 2015) and to 5070 TWh in 2013 (IEA, 2014) with generating capacity of 1690 GW (IEA, 2014). It was estimated that the CAGR will increase to 5.9% over the 2012 – 2015 period, amounting to 5 723 TWh in 2015 (World Bank, 2015).

In 2013 hydropower generating capacity expanded 41 GW. Due to attractive feed-in-tariffs (FITs) solar PV expanded to 39 GW. Onshore wind generating capacity increased by 34 GW that year (IEA, 2014).

Projected medium term growth for renewable electricity is 2245 TWh (45% growth). This will result in RE electricity generation of 7 213 to 7310 TWh in 2020 with generating capacity of approximately 2555 GW (World Bank, 2015; IEA, 2014). About 37% of this growth will likely be met with hydropower (including pumped storage) and onshore wind will account for 31% of new generation (IEA, 2014). Additions to power generation in non-OECD countries are expected to contribute up to 70% of new power generating capacity between 2013 and 2020. China will most likely be responsible for 60% of non-OECD growth and approximately 40% of the total growth. Other large contribution from non-OECD countries will likely be from Asia and the Americas (IEA, 2014).

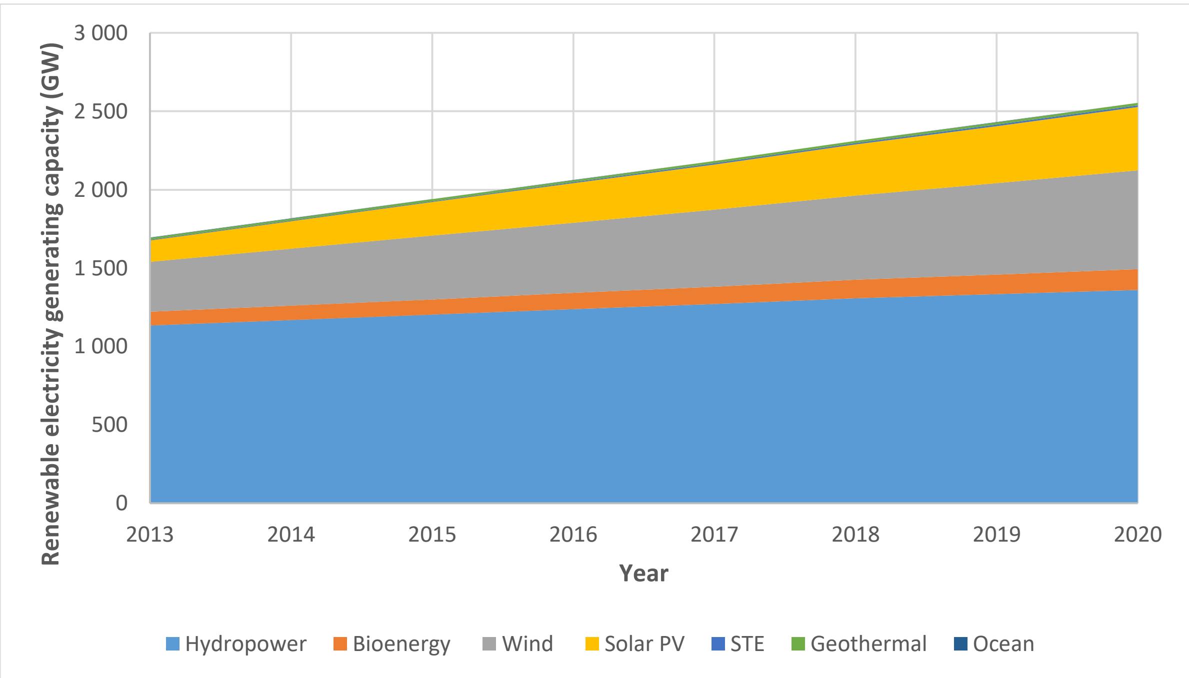

Figure 24: Renewable electricity generating capacity projections. Source: IEA (2014)

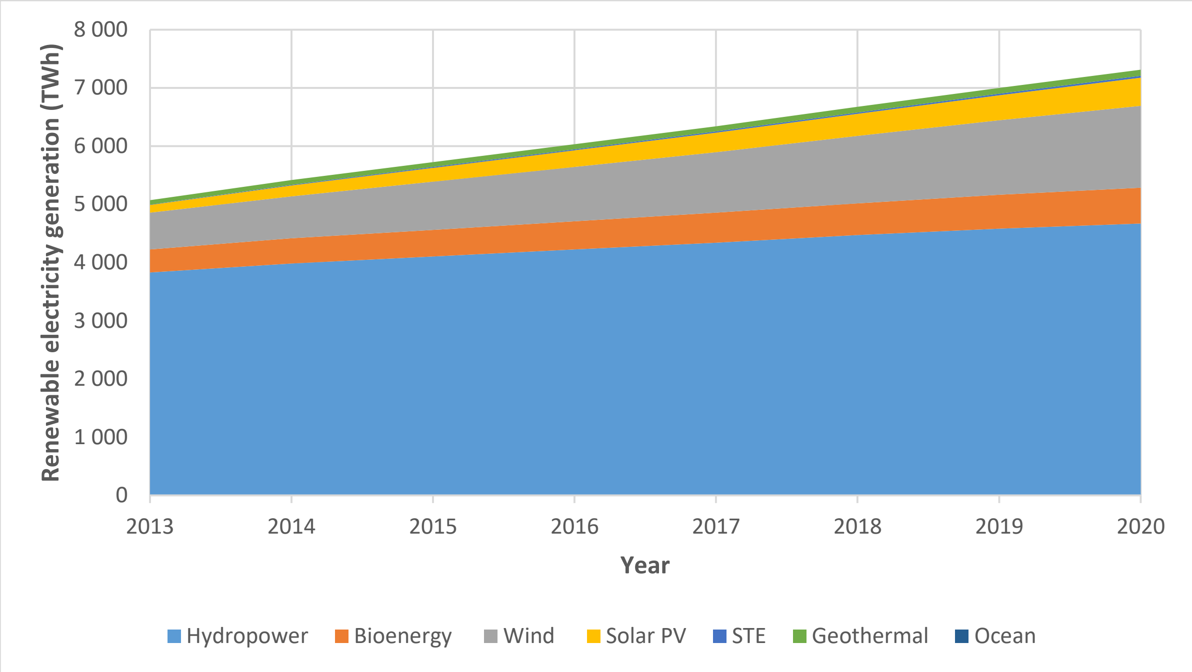

Figure 25: Renewable electricity generation projections. Source: IEA (2014)

A major challenge for the uptake of renewables in many parts of the world is that renewable energy can still not compete financially with more conventional forms of energy such as fossil fuels. This is in part due to the fact that environmental impacts of fossil fuels are not fully accounted for in their costing. High capital costs of RE is also a financial challenge in many situations (World Bank, 2013a). Policies therefore play a vital role in stimulating investment in renewables (IEA, 2014).

A 1.2 Renewable energy capacity and potential in South Africa

South Africa is rich in renewable energy sources. Solar, wind, biomass, and hydropower have the potential to make a significant contribution to the country's energy supply (Banks & Schäffler, 2006). The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP or REI4P) has set a target to install 17.8 GW of renewable electricity generation capacity between 2012 and 2030. The new capacity will be a mix of wind, solar, hydropower, biogas and biomass (Walwyn & Brent, 2015). In March 2015, the renewable electricity capacity that serviced the grid totalled 1 795 MW (Eskom, 2015a).

When the first bidding rounds concluded the REI4P initiative made little economic sense due to the average price of renewable electricity generation ($ 248/MWh) being almost three times higher than generation from conventional coal power stations ($ 71/MWh) (Walwyn & Brent, 2015). However, due to the escalating construction costs of the Medupi and Kusile coal power stations and the reduction in cost of both solar and wind power, it was estimated that RE electricity would reach grid parity by 2016, and be cost neutral by 2017 (Walwyn & Brent, 2015).

The REI4P has objectives other than simply increasing South Africa's RE generation capacity. Regional development, black economic empowerment, and local employment are also a priority. In the last rounds of bidding, local employment has increased, on average, by 18 new jobs per MW installed, in comparison with the first round when only 11 jobs were created per MW installed (Walwyn & Brent, 2015).

South Africa has some of the most promising renewable energy resources on the continent. Solar power, with the highest theoretical potential, and wind power are the prime candidates for future renewables (Krupa & Burch, 2011).

A 1.2.1 Solar power

South Africa has great potential for conversion of solar radiation into electricity. Daily solar radiation on average ranges from 4.5 to 6.5 kWh/$m^2$and South Africa receives approximately 2500 h of sunshine a year (Department of Energy, 2015b). The central and western parts of SA receive the highest radiation levels (see Figure 27). The southern and eastern regions have lower radiation levels, but these are still high in comparison to many European countries with high solar technology penetrations.

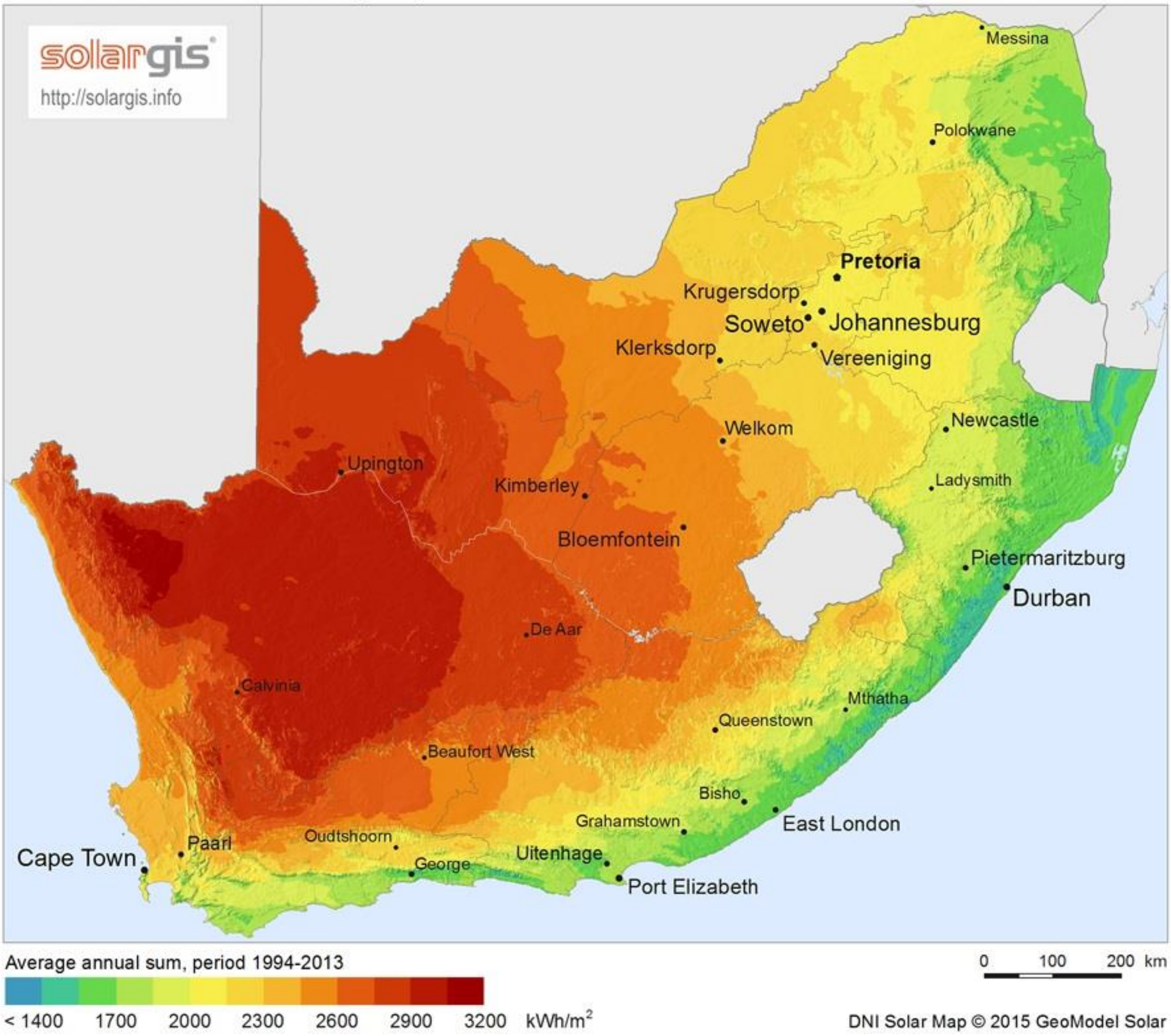

Figure 26: Direct Normal Irradiation map of South Africa. Source: SolarGIS (2017).

The SA Government's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has led to the construction and commissioning (in various stages of development) of 27 photovoltaic power installations with capacities ranging from 5 – 75 MW. Should all of these be operational in 2015, they will have a total generation capacity of approximately 900 MW and supply an estimated 1906 GWh of electricity (Giglmayr, Brent, Gauché & Fechner, 2015).

Table 31 contains a list of South Africa's solar power projects. Some of these are operational while others are still in the planning phase or under construction. The status symbols in Table 31 indicate construction phase (C), operational phase (O) and planning or preconstruction phase (A, P & F).

Table 31: Solar power projects in South Africa. Source: "Energy Project Database" (2016)

Project	Capacity (MW)	Status	Project	Capacity (MW)	Status
Photovoltaic Projects					
Adams Solar PV 2	82.5	C	Letsatsi Power Company	64	O
Aggeneys Solar Project	40	A,P&F	Linde	36.8	O
Aries Solar	9.7	O	Mulilo Prieska PV	75	O
Aurora	10.35	O	Mulilo Renewable Energy Solar PV De Aar	9.7	O
Bokamoso	68	A,P&F	Mulilo Renewable Energy Solar PV Prieska	19.9	O
Boshoff Solar Park	60	O	Mulilo Sonnedix Preiska PV	75	O
De Aar Solar Power	50	O	Pulida Solar Park	75	A,P&F
De Wildt	50	A,P&F	RustMo1 Solar Farm	6.8	O
Dreunberg	75	O	Sirius Solar PV Project One	75	A,P&F
Droogfontein 2 Solar	75	A,P&F	Sishen Solar Facility	74	O
Droogfontein Solar Power	50	O	SlimSun Swartland Solar Park	5	O
Dyason's Klip 1	75	A,P&F	Solar Capital De Aar (Pty) Ltd	75	O
Dyason's Klip 2	75	A,P&F	Solar Capital De Aar 3	75	O
Electra Capital Paleisheuwel Solar Park	75	O	Solar Capital Orange	75	A,P&F
Greefspan PV Power Plant	10	O	Soutpan Solar Park	28	O
Greefspan PV Power Plant No.2 Solar Park	55	A,P&F	Tom Burke Solar Park	60	O
Herbert PV Power Plant	19.9	O	Touwsrivier Project	36	O
Jasper Power Company	75	O	Upington Solar PV	8.9	O
Kalkbult	72.5	O	Vredendal	8.8	O
Kathu Solar Energy Facility	75	O	Waterloo Solar Park	75	A,P&F
Konkoonsies II Solar Facility	75	A,P&F	Witkop Solar Park	30	O
Konkoonsies Solar	9.7	O	Zeerust	75	A,P&F
Lesedi Power Company	64	O			
Concentrated Solar Power Projects					
Bokpoort CSP Project	50	O	KaXu Solar One	100	O
Eskom CSP	100	A,P&F	Khi Solar One	50	O
Ilanga CSP 1	100	C	Redstone CSP	100	A,P&F
Kathu Solar Park	100	A,P&F	Xina CSP South Africa	100	C

An important point to take note of is that PV power was predicted to cost less than power generated from coal by the beginning of 2015 (Walwyn & Brent, 2015). The REIPPPP tariffs for bidding windows 4 and 4B were respectively 78.6 c/kWh and 90.4 c/kWh for solar PV electricity (GreenCape, 2016).

A 1.2.2 Wind power

South Africa is host to a number of wind farms including Darling National Demonstration Wind Farm, a wind farm near Caledon, another near Jeffreys Bay and one close to Hanover. The Sere Wind farm (100 MW), Eskom's first utility-scale wind farm, has also been operational since the end of March 2015 (Eskom, 2015a). Table 32 presents a summary of the turbine capacities at each wind farm ("Wind Farms", 2016). Some of these farms are still under construction and thus not fully operational yet.

Table 32: South African wind farm capacities and annual generation

Wind farm	Capacity (MW)	Wind farm	Capacity (MW)
Klipheuwel	3.2	Jeffery's Bay	138
Darling	5.2	Khobab	140.3
Amakhala Emoyeni	134.4	Klipheuwel	3.2
Chaba	21.5	Kouga	80
Coega	1.8	Loeriesfontein 2	140.3
Cookhouse	138.6	Nelson Mandela Bay Stadium	1.8
Copperton	102	Nobelsfontaine	73.8
Darling	13.3	Noupoort	80.5
Dassiesklip	27	Sere	105.8
Dorper	100	Soetwater	141.9
Gibson Bay	111	Tsitsikamma	95.3
Gouda	138	Waainek	24.6
Grassridge	60	West Coast One	94
Hopefield	66.6		

Various studies have been conducted to construct wind atlases for South Africa. These include G7, WASA and EScience. The Northern Cape, Western Cape, Eastern Cape and KwaZulu-Natal provinces have favourable locations for wind power generation due to the high coastal wind speeds (Department of Trade and Industry, 2015). Figure 28 illustrates a wind resource map of selected areas in South Africa.

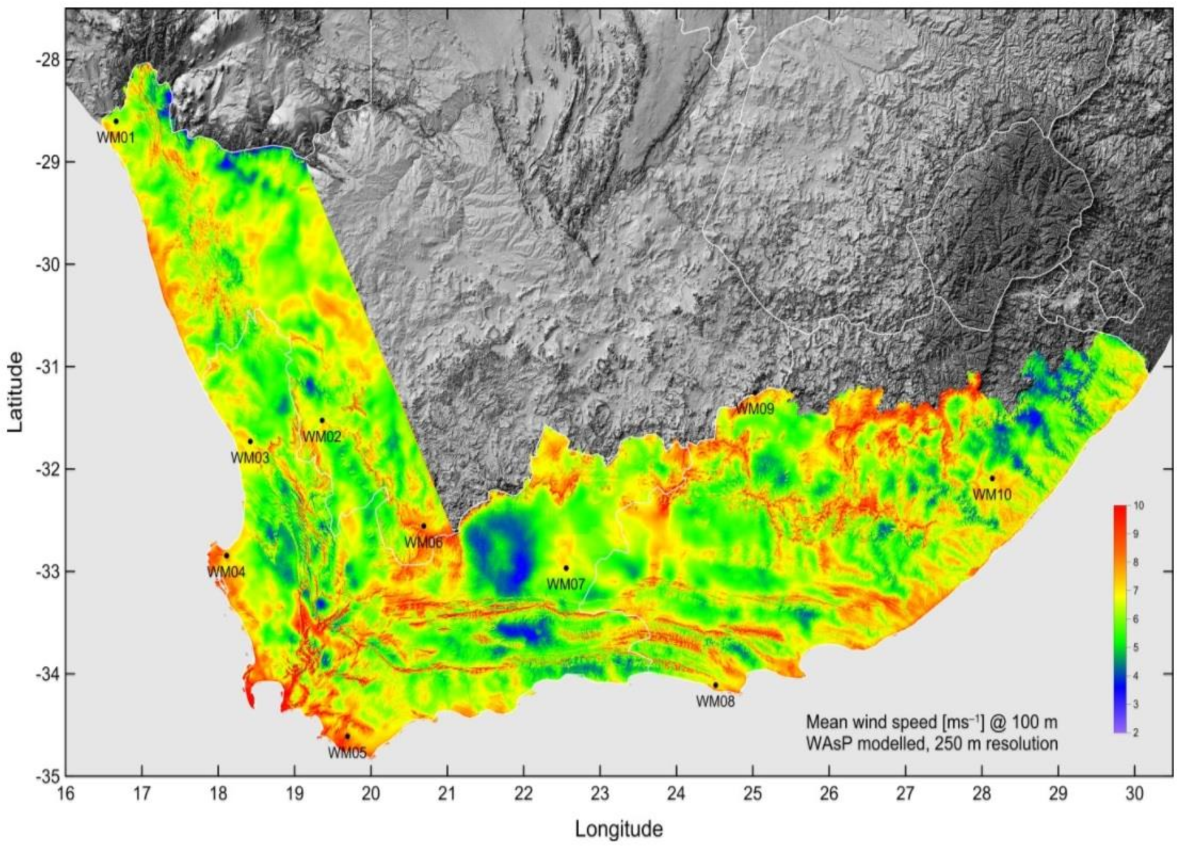

Figure 27: Mean wind speed map of South Africa. Source: SANEDI (2017)

Using a pessimistic and optimistic scenario, it is estimated that South Africa has wind capacity potential ranging from 6 GW (20 TWh per year) to 56 GW (157 TWh per year) based on the respective scenarios. The more realistic scenario resulted in 26 GW (80 TWh per year). Other studies have given a wider range of possibilities for generating capacity of 0.5 GW to 70 GW (Szewczuk, 2010). Assumptions that were taken into account when these scenarios were modelled include factors like distance from existing infrastructure – transmission lines and roads, hub heights, and capacity factors.

The original IRP (Integrated Resource Plan) for 2010 – 2030 set a target of 9 200 MW to be generated from wind power installations. In 2013 the IRP was updated and the target was adjusted downward to 4 360 MW (Department of Energy, 2011, 2013). Following the three bidding windows of the REIPPPP initiative, 22 wind power projects have been awarded a total of 1 984 MW of generating capacity (Department of Trade and Industry, 2015). The remaining capacity is yet to be allocated.

The cost of wind power has declined rapidly over the three REIPPPP bidding rounds. Bid window 3 of the REIPPPP reflected capital investment requirements of R 7.9 mil/MW for wind power capacity and average electricity tariffs were R 0.74/kWh compared to the first bid window's R1.28/kWh (Department of Trade and Industry, 2015).

A 1.2.3 Geothermal power

Tectonically South Africa is relatively stable due to the Kaapvaal Craton underlying it. The Kaapvaal Craton in turn is also underlain by a chemically deplete and exceptionally thick mantle lithosphere. The structure is relatively immune to melting and has low heat conductivity. Much of the heat is therefore not conducted to the surface, but away towards areas where the mantle lithosphere is thinner or less depleted. The result is that heat flow to the surface is low and so are the geothermal gradients. This is the fundamental reason that geothermal energy is not considered a viable option for South Africa and is thus not considered by NERSA (De Wit, 2014).

Studies have however been conducted that suggest power generation in the form of low enthalpy geothermal energy extraction is possible from temperatures in the range of 100 to 200°C (at depths of 2 – 3 km). These conditions are met at certain locations in the Limpopo Province. The studies conclude that this method of power generation will be expensive relative to other forms of renewables, and will heavily rely on tax incentives to be viable (De Wit, 2014).

A 1.2.4 Biomass power

Although the forestry biomass of South Africa alone was estimated to have potential energy of 242 PJ/year to 1 200 PJ/year by 2020 (Stecher, Brosowski & Thran, 2013), biomass power generation has a very small capacity in the South African context. The only major generators are the paper pulp and sugar industry, which has capacities of approximately 170 MW and 245 MW respectively (Davidson, Winkler, Kenny, Prasad, Nkomo, Sparks, Howells & Alfstad, 2006).

The little interest in biomass power was also reflected in the REIPPPP bidding rounds. In both round 1 and round 2, no biomass power was allocated. Only in round 3 of the bidding process was 16 MW of biomass power allocated to a single project. Sappi was also selected as a preferred bidder for biomass power for the fourth round of bidding (Sappi, 2015).

However, SAEON and South Africa's department of energy have finished the Bio-Energy Atlas for South Africa in 2017. With this new information tool, biomass might move closer to reaching its potential as an energy resource. Figure 29 presents the occurrence of invasive alien plants across South Africa.

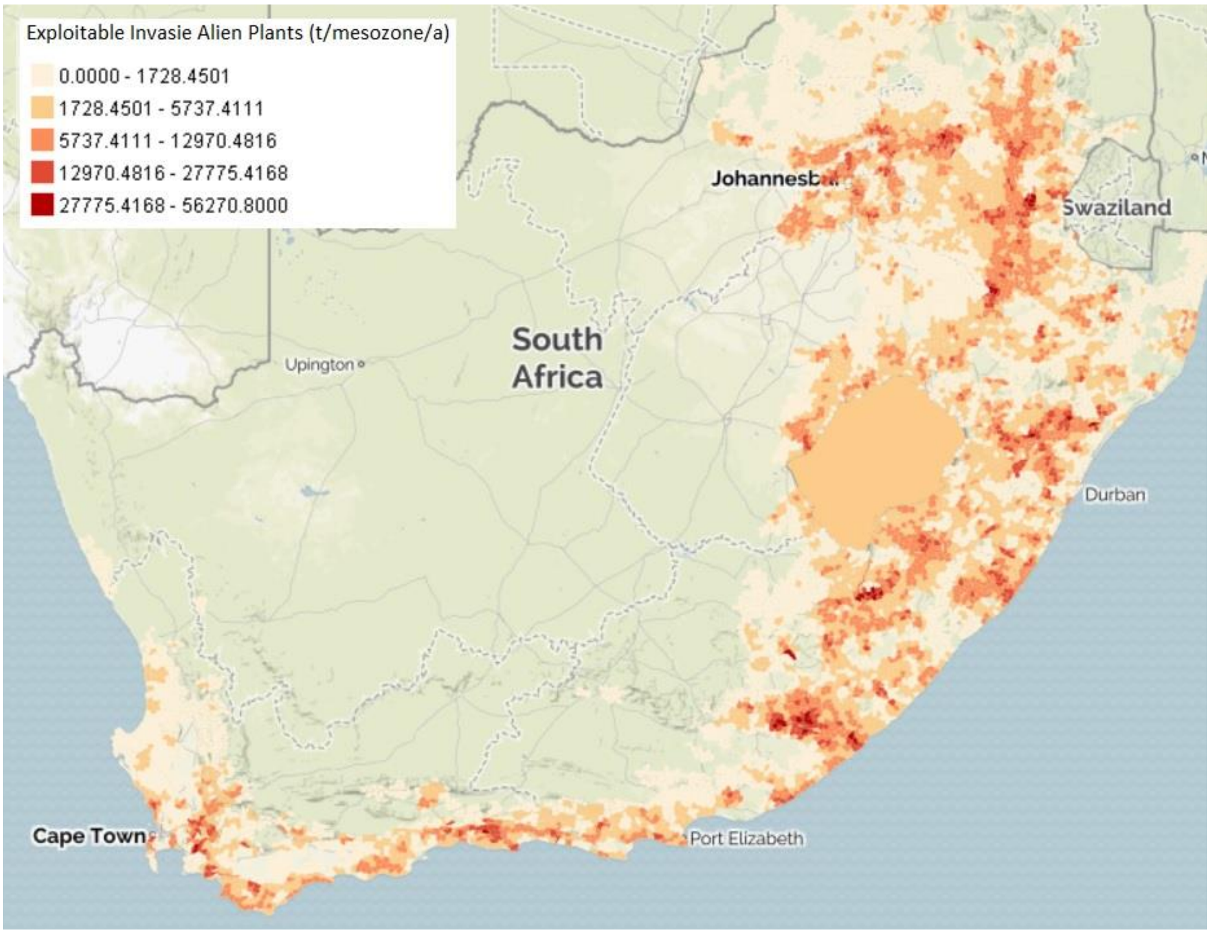

Figure 28: Invasive alien biomass in South Africa. Source: SAEON (2017)

Obstacles that might influence the use of biomass as a widely used energy source were discussed by Hugo (2015):

- Biomass availability is low and compared to global standards, so is biomass productivity in South Africa due to rainfall constraints. Competition with agricultural land will further constraint the production of energy crops in many parts of the country.
- Using firewood is potentially problematic because it is a cheap source of fuel for poorer households. Data regarding the use of firewood as fuel is usually of poor quality or unavailable.
- Many of the current processing technologies are not mature and thus not likely to be commercially useful in the near future.
- Many feasibility studies only consider the current state of affairs when considering the feasibility of the projects. Factors such as the exchange rate, inflation, fossil fuel prices and

economic growth may have unforeseen impacts that cause operations to become unsustainable.

- Eradication of IAPs have the best medium-term potential as a biomass energy source, but the supply will probably last only 20 years.

Appendix B: Overview of Renewable Electricity Technologies

B 1.1 Biomass Power

Before fossil fuels were used all around the world, the primary fuel source for heat energy was biomass, used in combustion (Kumar, Jones & Hanna, 2009). Today, biomass energy utilisation is increasing due to a number of drivers including a contribution to poverty reduction in developing countries, energy demands that can be met at all times, energy can be delivered in various forms, it can be regarded as CO_2 neutral and it has various positive environmental impacts. Some of the environmental benefits include the restoration of unproductive land, increasing biodiversity, soil fertility and water retention (Karekezi, Lata & Coelho, 2004).

Many types of biomass can be considered to be an indirect source of solar power. When plants grow they convert carbon dioxide, water and sunlight into sugars and other compounds. Plants are to some extent a battery where energy is stored. This energy can be released again through a combustion process (or other processing routes).

Biomass energy (bio-energy) has a wide field of applications. Unlike other renewables such as solar power, the sustainability of biomass energy must be evaluated on a case-by-case basis. Production methods, conversion processes, feedstock, infrastructure, location etc. have to be taken into account (World Bank, 2013a).

The traditional use of biomass is simple combustion. The resulting heat is used for space heating or cooking. Modern methods of biomass conversion have three main products namely liquid fuels, heat and electricity. The technologies used for biomass conversion can be grouped into bio-chemical conversion (fermentation, anaerobic digestion), thermo-chemical conversion (pyrolysis, gasification, combustion) and mechanical extraction. Factors like biomass availability, desired end product, environmental standards and economic conditions will impact the technology selected and processing route (Saidur, Abdelaziz, Demirbas, Hossain & Mekhilef, 2011). Other local factors that must be taken into consideration when choosing a technology include emission standards, fuel prices and electricity sales revenue (Vandenbroek, 1996).

Bio-energy can come from a variety of biomass sources such as forests, residues from sawmills and similar operations, agricultural wastes as well as dedicated crops (woody or herbaceous) (Keoleian &

Volk, 2005), but dedicated energy crops have a higher long-term potential than residue and waste sources (Bazmi & Zahedi, 2011).

64% of biomass based energy is derived from wood and wood wastes. MSW accounts for approximately 24% of biomass energy production and agricultural waste and landfill gas contribute 5% each (Demirbas, Balat & Balat, 2009). Wood and wood waste may even contribute as much as 87% of global biomass energy (Petrie, 2014). Biomass sources are often dispersed over large areas, biodegradable and generally has a low bulk density, especially when compared to coal. This creates problems in storing, handling and transporting biomass (Ganesh & Banerjee, 2001) and also leads to dis-economies of scale (Bazmi & Zahedi, 2011).

Biomass has huge potential and could ensure a sustainable energy and fuel supply for the future. It is therefore critical that biomass is utilized in a sustainable manner, especially in developing countries (Demirbas *et al.*, 2009).

B 1.1.1 Thermo-chemical conversion technologies

When biomass material has a moisture content below 50% is it generally suitable for “dry” conversion processes (Caputo, Palumbo, Pelagagge & Scacchia, 2005) namely: pyrolysis, gasification and combustion.

B 1.1.1.1 Pyrolysis

Pyrolysis is defined as the thermal decomposition of organic matter in the absence of oxygen (Saidur *et al.*, 2011). Pyrolysis products are grouped into permanent gases, pyrolytic liquids and char (Demirbas *et al.*, 2009).

The three main constituents of woody biomass is hemicellulose, cellulose and lignin. The high fuel-to-feed ratio achieved in pyrolysis process makes it the most efficient biomass conversion process. It is considered to be the most capable of competing with fossil fuels and eventually replacing them (Demirbas, 2002).

Chiaramonti, Oasmaa and Solantausta (2007) present some of the advantages of using pyrolysis liquids (produced with fast pyrolysis) as fuel:

- Pyrolysis produces the lowest cost liquid biofuel.
- There is potential for using pyrolysis liquids in both small and large scale power plants (large scale plants would use a co-firing approach).
- Operations such as solid biofuel handling can be decoupled from utilisation because the liquid fuels are easier to transport and store.
- Pyrolysis fuels have a higher energy density than the fuel gas produced in atmospheric gasification processes.
- Existing power plants can be modified to use pyrolysis liquids as fuel.

Challenges in using pyrolysis liquids as fuels are mainly due to their unusual fuel properties (acidic, high concentrations of solids and chemically dissolved water, high viscosity, unstable) and variations quality. Additives and amount of water present in the pyrolysis liquid will influence the fuel's density, viscosity and heating value. The biomass feedstock will also have a large influence on the product liquids (Chiaramonti *et al.*, 2007). Typically a bio-oil produced from woody feedstock will consist of 30% water, 20% ketones and aldehydes, 30% phenolics, 10% alcohols and the remaining 10% will consist of miscellaneous compounds (Hassan, Yu, Ingram & Steele, 2009).

Pyrolysis can be divided into different classes depending on the operating conditions. The three classes and their respective operating conditions are briefly described in Table 33.

Table 33: Pyrolysis types general operating conditions. Source: Demirbas and Arin (2002)

Pyrolysis type	**Operating conditions**			
	Temperature (K)	**Heating rate (K/s)**	**Solids residence time (s)**	**Particle size (mm)**
Conventional	550 – 950	0.1 - 1	450 - 550	5 – 50
Fast	850 - 1250	10 -200	0.5 - 10	< 1
Flash	1050 – 1300	> 1000	< 0.5	< 0.2

Only fast pyrolysis will be discussed in the rest of this section since commercial success has already been achieved for electricity production from fast pyrolysis products (Bridgwater, 2004). When using fast pyrolysis it is recommended that either entrained flow or fluidised bed reactors are used when the biomass feed is available as fine particles or approximately sawdust size (Demirbas & Arin, 2002; Hassan *et al.*, 2009).

The liquid product produced by biomass pyrolysis has many names including bio-oil, pyrolysis oil, wood liquids, wood oil, wood distillates, bio-fuel-oil and bio-crude-oil to name but a few. Power can be generated using pyrolysis liquids as fuels in (diesel) engines, gas turbines, boilers and sterling engines (Bridgwater, 2004). Co-firing the oil with coal is also possible but is only used in large scale coal power plant.

B 1.1.1.2 Gasification

Biomass gasification can be described as high temperature, partial oxidation to produce gaseous fuels with a typical calorific value ranging from 4 – 6 MJ/m^3(Saidur *et al.*, 2011). During gasification biomass is converted to a mixture of CO, H_2 and CH_4 and other light hydrocarbon molecules. Tar and char is also formed during gasification due to incomplete biomass conversion (Kumar *et al.*, 2009). The product gas can be used to generate heat or steam when combusted or it can be used to generate electricity through gas turbine cycles (Caputo *et al.*, 2005). These gasifier/gas turbine systems are projected to reach efficiencies of 40 – 45% for electricity conversion (Demirbas *et al.*, 2009) and conversion efficiencies as high as 50% could be reached through utilization of integrated gasification/combined gas-steam cycles (Caputo *et al.*, 2005). For gasification to be economical, a minimum generating capacity of 5 kWe must be met (Kirubakaran, Sivaramakrishnan, Nalini, Sekar, Premalatha & Subramanian, 2009).

A biomass gasification operation can usually be divided into four steps namely pre-treatment, gasification, gas clean-up and gas utilisation as illustrated in Figure 30.

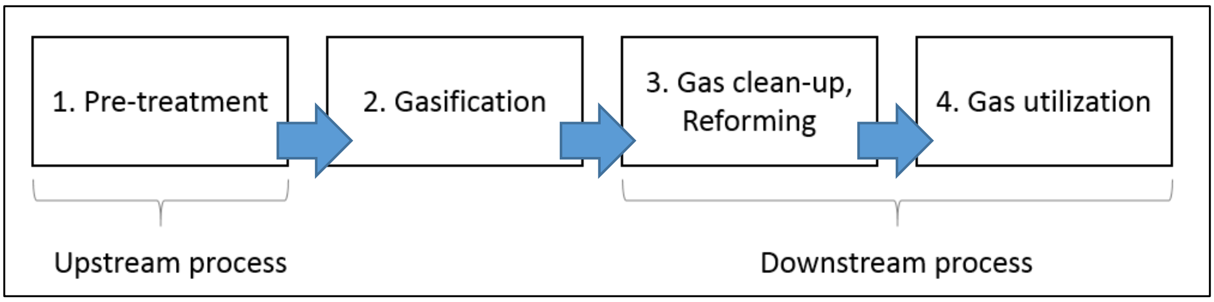

Figure 29: Biomass processing chain. Source: Kumar *and others* (2009)

Gasification reactions take place at temperature of 600 – 1000 °C. Depending on the desired products, air, oxygen, nitrogen, steam or a mixture of these gases can be used as oxidants. Although air is the cheapest, it would decrease the heating value of the product syngas due to high nitrogen concentrations (Wang, Weller, Jones & Hanna, 2008).

Various gasifier types are commercially available. Popular options include a fixed bed and fluidized bed gasifiers. Biomass type and flow rate, design type, gasification temperature, catalyst amount and catalyst type as well as the oxidant used are some of the main operating parameters for gasifiers (Kumar *et al.*, 2009).

Power production

Biomass plants can be designed to produce heat and power (CHP). Gasification has advantages over direct combustion: higher efficiencies can be reached in fuel-gas systems such as gas turbines or gas engines, because gas fuels burn more efficiently than solids overall efficiency in gasification is higher than combustion and contaminants that cause NO_x and SO_x emission can be removed (Kumar *et al.*, 2009).

Syngas produced during the gasification process can be utilised for power production in a number of ways. Combusting the syngas to generate steam and drive a steam turbine which in turn generates electricity is one method. When syngas combustion is used the generating efficiency will be limited by the theoretical efficiency limit of the steam turbine (Wang *et al.*, 2008). Alternatively the syngas be fed into a gas turbine or gas engine for power generation. For this approach the syngas needs a high heating value and very low concentrations of tar and particles (Wang *et al.*, 2008).

Various commercial configurations for gasification are available but for systems with capacities ranging from 5 MW – 300 MW (Caputo *et al.*, 2005).

B 1.1.1.3 Combustion

Traditional direct biomass combustion in an open fireplace (with the purpose of heating) is a very inefficient operation (Demirbas *et al.*, 2009). Not only is combustion responsible for 97% of biomass energy production (Zhang, Xu & Champagne, 2010), but it is also technically the simplest form of biomass power generation. The basic power generation process for biomass is similar to coal-fired power generation. The biomass is combusted, heat is generated and used to generate stream. The steam is then used to drive a turbine, which in turn drives a generator to produce electricity. Net conversion efficiencies for biomass combustion plants are in the range of 20% – 40% (Caputo *et al.*, 2005).

Waste materials that are used as fuels for combustion include sawdust, pulp mill liquor, hog fuel, cardboard, food processing waste, municipal garbage (Saidur *et al.*, 2011).

B 1.1.2 Bio-chemical conversion technologies

Generally, biomass feed material with a moisture content of over 50% is used in "wet" conversion processes like fermentation and anaerobic digestion (Caputo *et al.*, 2005). Biological methods used to convert lignocellulosic biomass are still relatively expensive and inefficient compared to thermochemical methods (Lin & Tanaka, 2006).

B 1.1.2.1 Fermentation

Fermentation processes are primarily used to convert biomass to ethanol. Fermentation feedstock is typically material with a high sugar or starch content like corn, grains or sugarcane (Balat, 2006). The feed material is usually crushed to extract the sugars which are then mixed with yeast and water and heated in a fermenter where the sugars are converted to alcohol (mostly ethanol). The overall reaction for the conversion of glucose (a sugar) to ethanol (CH_3CH_2OH) is given in Equation 98.

Equation 98

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

The liquid product from the fermenter is distilled in a distillation process where the water and alcohol is separated and the ethanol vapour is condensed back into a concentrated liquid (Caputo *et al.*, 2005). The liquid bio-ethanol can technically utilised in power generation, but it is generally used as a transportation fuel.

B 1.1.2.2 Anaerobic digestion

Anaerobic digestion is a process that occurs naturally in landfills, but smaller scale anaerobic digesters can also be designed to perform a similar task.

Municipal solid waste is a popular feedstock for anaerobic digesters due to the high moisture content, which is often undesirable in other technologies (Caputo *et al.*, 2005). High moisture herbaceous plants that are also suitable for anaerobic digestion include vegetables, sugar cane, corn, cotton, sugar beet and sorghum (Demirbas *et al.*, 2009).

The contents of most landfills include a large portion of organic matter from garden waste, household waste and industrial waste. After refuse has been deposited in a landfill, open to the atmosphere, the organic matter starts to decompose aerobically. Once the landfill is covered and the oxygen is exhausted, organic material decomposed anaerobically and the production of biogas or landfill gas begins (Willumsen, 1990). Municipal solid waste (MSW) and organic waste that is subjected to these biodegradation processes produce a gas consisting of methane (50 – 55%) and carbon dioxide (40 - 45%) (Johari, Ahmed, Hashim, Alkali & Ramli, 2012). The remaining gas product consists of approximately 5% nitrogen and other gases (Jaramillo & Matthews, 2005). Both of these gases are greenhouse gases (GHGs) that contribute to global warming when released into the atmosphere. Methane is however up to 25 times more potent than carbon dioxide when considering its impact on global warming (He, Herman, Minet & Tsotsis, 1997).

Product gas composition will vary depending on a number of factors including system design and feed material. Methane content of the product gas varies between 55 and 95% for some state-of-the-art systems (Balat, 2006). This product gas mixture can be used as a fuel without much processing, expect for the removal of water an particulate impurities, or upgraded to almost 100% pure methane and used as natural gas substitute (Willumsen, 1990). 350 – 400 m^3 of product gas can be expected per tonne of waste when a typical landfill composition is assumed (Willumsen, 1990). Other sources indicate that 432 000 cubic feet of gas can be produced from every 1 million tons of MSW deposited in a landfill. This will amount to approximately 0.8 MW of electric power generated (Simon, Singleton & Carter, 2007). The gas is collected by applying a vacuum to a series of perforated pipes buried in the landfill site (Ismail & Abderrezaq, 2007). These pipes can be horizontal or vertical and are sometimes referred to as wells.

As the population in an area grows, human activity will grow and as a result the amount of waste generated will also increase (Agamuthu, Khidzir & Hamid, 2009). It is therefore important to find sustainable ways to manage waste. Utilising landfill gas is one option that can contribute to more sustainable waste management.

A project was launched in the eThekwini Municipality with the Clean Development Mechanism where landfill sites were used for power generation. One operation came online in 2006 and the other in 2009. The study concluded that it was not viable to generate power from small to medium (500 – 1000 tonnes of waste per day) landfill in Africa, at least under the conditions at that time, without a renewable energy feed-in-tariff or a similar alternative (Couth *et al.*, 2011).

B 1.1.3 Mechanical extraction

Mechanical extraction techniques are mostly used for the production of bio-diesel. Due to the relatively high cost of bio-diesel when compared to fossil fuels, mechanical extraction is a strongly uncompetitive conversion option (Saidur *et al.*, 2011).

B 1.1.4 Biomass pre-treatment

Often raw biomass cannot be directly processed. Before the biomass is converted to energy or fuel a number of pre-treatment steps are required, depending on the conversion technology and desired end product. This section will discuss the various pre-treatment options for thermochemical conversion plants.

B 1.1.4.1 Drying

Depending on the process route followed, biomass feed material has minimum or maximum moisture content requirements. For gasification the moisture specification range from 10 – 20% (Cummer & Brown, 2002). When moisture content is too high, which is often the case for freshly harvested biomass (with moisture content up to 60%) drying is required (Cummer & Brown, 2002).

Drying processes energy intensive and will affect the overall process energy efficiency (Kumar *et al.*, 2009). Waste heat from other parts of the process (e.g. turbine exhaust gas, by-product combustion, producer gas) can be used to reduce energy required for drying. Temperatures and oxygen content must be low enough to avoid ignition of the material being dried.

Factors that will influence the type of dryer used in the system include drying capacity, feedstock particle size as well as the type of biomass (herbaceous or woody) (Cummer & Brown, 2002).

B 1.1.4.2 Size reduction

Gasification reaction rate and the composition of product gases are influenced by the feed material's particle size (Huber, Iborra & Corma, 2006). Typically wood chippers or mills are used.

B 1.1.4.3 Densification

Due to biomass' low density (relative to coal), densification is often required (Kumar *et al.*, 2009). Densification is used to upgrade the biomass fuel quality by increasing energy density. Densification also has other benefits for the fuel such as decreased handling, storage and transportation costs (Saidur *et al.*, 2011).

B 2.1 Solar Power

Solar power technologies convert energy from the sun to heat or electricity. Applications for solar heating include water heating, process heat and heat for cooking. The two main technology classes for electricity generation are photovoltaics (PV) and concentrated solar power (CSP). PV technology utilises the photovoltaic effect to convert sunlight directly into electricity. CSP focuses the sun's heat energy which can then be used electricity generation (Singh, 2013).

B 2.1.1 Photovoltaics

The four major types of PV technology are: thin film, crystalline, nanotechnology based and compound semiconductors. Silicon was used to produce the first generation of PV cells with a crystalline structure. These cells are combined to form a PV module. Although the technology is not new it is continuously improved to achieve higher efficiencies and capabilities. Currently crystalline PV modules have an efficiency of 15% - 24.7% and a market share of approximately 80% (El Chaar *et al.*, 2011). Thin film technology has the potential to produce cheaper modules by reducing the amount of material used. The thin film PV panels are produced by depositing a layer (10µm thick) of certain materials onto a substrate, usually stainless steel or glass. Efficiencies range from 4% to 20%. Compound semiconductor cells have efficiency ranges between 5% and 30%. Nanotechnology based solar cells have a wide range of efficiencies. Carbon nanotube cells are relatively new and reach efficiencies of about 4%, but hot carrier solar cells can have efficiencies of up to 66% (El Chaar *et al.*, 2011).

The major advantage of PV is that it is a low maintenance, environmentally friendly and non-polluting (El Chaar *et al.*, 2011). Solar power in general has the advantages of an abundant energy source.

The greatest barrier to implementation of PV systems is the fact that the technology can only generate electricity when the sun is shining. Electricity generated from solar PV is usually difficult and expensive to store. Therefore the main market for PV electricity is grid connected applications (Banks & Schäffler, 2006). Some storage options include super capacitors, fuel cells, batteries and flywheels.

B 2.1.2 Concentrated solar power

Concentrating solar power plants use reflective surfaces to focus heat from the sun to heat a heat transfer fluid (HTF). The heat energy from the HTF can be used to generate steam to drive a turbine which can then drive a generator to generate electricity. CSP plant generating capacity can range from multi-megawatt to several gigawatt (GW). Three types of CSP technology is available today: Parabolic trough, power tower systems and dish concentrators. Thermal storage is also possible in the form of molten salts, which can allow CSP plants to generate electricity 24 hours a day (Banks & Schäffler, 2006). Alternatively the water-steam cycle that powers the turbine can be driven by burning fossil fuels or biomass during bad weather periods or at night (Quaschning & Muriel, 2001).

B 2.1.2.1 Parabolic trough

Parabolic troughs are used to reflect sunlight onto a tube in the troughs focal point. The focused light heats a fluid in the tube to temperatures of approximately 400 °C. The fluid can be used to provide process heat or to produce steam for electricity generation in a steam turbine. Parabolic trough power generation plants typically have generating capacities between 50 and 200 MW (Banks & Schäffler, 2006).

B 2.1.2.2 Power towers

Heliostats focus sunlight onto a receiver mounted on a central tower. The light focused on the receiver is used to heat a heat transfer fluid (which can reach 1000 °C) that can be used to generate steam for a steam turbine and generator to generate electricity. Each heliostat can be controlled with a computer and sun tracking system to orientate the it on two-axes for maximum reflection onto the receiver (Quaschning & Muriel, 2001). Typical generating capacities are comparable with parabolic trough systems (Banks & Schäffler, 2006).

B 2.1.2.3 Dish concentrators

Dish concentrator work on the same basic principle as the other CSP technologies but usually on a smaller scale (50 W – 50 kW). A parabolic dish is used to focus sunlight onto a receiver where electricity can be generated using a heat engine, typically a sterling engine (Banks & Schäffler, 2006).

B 3.1 Wind Power

Wind has been used for windmills for thousands of years before wind turbines were introduced in modern times to generate electricity. Installations for wind power generations are however only practical where strong winds blow frequently (Department of Energy, 2015c). Modern wind power technology utilises turbines that harvest kinetic energy from the wind to drive generators and then converts that energy to electric power. Most modern day turbines designs use three blades with a horizontal axis. As with many other renewable energy sources, wind power can suffers from intermittence. Wind speeds can fluctuate on various time scales from minutes and hours to seasons and years (Haydt, Leal, Pina & Silva, 2011).

B 3.1.1 On-shore wind power

Wind turbines can be installed onshore or off-shore. Onshore wind power technology is a more mature than off-shore and average turbine generating capacity ranges from 1.5 – 2.5 MW per turbine. Although larger designs are in operation the average wind generator's tower and blade diameter both range from 50 m to 100 m (Intergovernmental Panel on Climate Change, 2012). Wind turbines usually require wind speeds of 2.5 – 25 m/s for operation (Gül & Stenzel, 2005).

B 3.1.2 Off-shore wind power

Off-shore wind turbines are generally larger than onshore versions. The technologies are very similar but off-shore installations have challenges with logistics and higher maintenance. This type of wind power is attractive for a number of reasons including: additional wind resources, stronger and more consistent winds, and better economies of scales when larger turbines are used. 5 to 10 MW turbines will likely be commonplace as the off-shore market develops further (Intergovernmental Panel on Climate Change, 2012).

B 4.1 Hydro Power

B 4.1.1 Conventional hydro power

Hydropower can usually be classified into large or small hydropower. Although no official measure is used to differentiate between them, installations with generating capacity below than 10 MW are generically considered as small hydropower. Sometimes these installations are further classified into micro- and pico-hydropower installations with upper capacity limits of 300 kW and 10 kW respectively (Klunne, 2013).

Hydro power is a mature and well established technology. The first hydro power station, with generation capacity of 12.5 kW, was commissioned in 1882. It was estimated that global hydro power generation has a technical potential capacity of 3 721 GW and 14 576 TWh per year (Intergovernmental Panel on Climate Change, 2012). The existing installed hydropower capacity is less than a quarter of that (926 GW) (Intergovernmental Panel on Climate Change, 2012).

Hydro power plants can be classified into three main groups: run-of-river, pumped storage and storage. Run-of-river (RoR) has no storage capacity and is dependent on the rivers intake basin. Power production may therefore decrease when river's flow is reduced due to seasonal changes etc. For larger rivers RoR installations may be used for base load power generation (Intergovernmental Panel on Climate Change, 2012).

B 4.1.1.1 Pumped storage

Storage and pumped storage hydro power involves one or two dams for water catchment. During periods of low demand (or low cost), electric power can be used to pump water for the lower of the two reservoirs to the higher one. When demand (or purchase price of electricity) increases again, the water from the higher reservoir can be used to drive a turbine and generator for power generation to meet that demand (Kucukali, 2014). Hydropower is a mature technology and also a dominant form of energy storage available today (Punys, Baublys, Kasiulis, Vaisvila, Pelikan & Steller, 2013). Other advantage of pumped storage schemes is their quick response times, which allows them to compliment other renewable energy sources with high variability like solar and wind power (Kucukali, 2014).

B 4.1.2 Ocean power

Electricity can be generated from the ocean using various methods. Tides, ocean circulation, waves on the ocean surface and gradients (both thermal and salinity gradients) can be utilised for electric power generation. Some of these methods are more predictable than other but offer great potential for sustainable energy supplies for countries that have access to ocean resources (Bahaj, 2011).

B 4.1.2.1 Tide power

Kinetic energy in marine currents are relatively diffuse in most locations around the world, but is concentrated by certain topographies such as straights and islands. Because this type of energy is driven by gravity and planetary motion it is highly predictable (Bahaj, 2011).

Various types of turbines are used for tidal power generation and the principles are similar to wind power generation (Patel, 2008). When turbines are used for power generation, the density of the fluid flowing through the turbine will impact the power of the flow. Water is about 800 times denser than air, which means lower fluid velocities are required for power generation (Bahaj, 2011).

B 4.1.2.2 Wave power

It was estimated that wave energy could supply 8000 – 80 000 TWh of electrical power per year and will provide approximately 1.2 million jobs by 2050 (Lin, Bao, Liu, Li, Tu & Zhang, 2015).

Various systems exist that can convert wave energy into electrical power. Popular options include rafts, point absorbers, oscillating water columns, ducks and pendulums (Lin *et al.*, 2015).

The Pelamisis is a raft type wave energy converter. As the name suggests, the device floats on the ocean surface. It consists of different segments connected hinged joints. As waves propagate towards the shore (and along the length of the device), relative movements of the individual, interconnected segments of the Pelamisis drives hydraulic motors and generators that converts the kinetic energy of the waves to electricity. For more information and reviews of wave power technologies the following sources can be consulted: (Patel, 2008), (Kerr, 2007), (Intergovernmental Panel on Climate Change, 2012).

Hydraulic systems used for wave power generation have various short term storage options available to ensure smooth power production. These include batteries, super capacitors, flywheels and compressed air (Lin *et al.*, 2015).

In the past, countries have placed more emphasis on off-shore wind power technology than ocean power. This is mostly due to the fact that wind power technology is much more mature and still economically favourable. Efficient energy extraction from ocean waves requires further research and development before this kind of technology will become more economically feasible (Nader, Zhu & Cooper, 2014).

One major disadvantage of certain ocean power technologies (wave energy converters in particular) is pollution due to leakages of hydraulic fluids. Before these types of systems can be implemented at large scale, the pollution problems have to be solved (Lin *et al.*, 2015).

B 5.1 Geothermal Power

Geothermal power is derived from thermal energy originating in Earth's interior. Wells are often used to extract this heat energy at sites where geothermal reservoirs are close enough to the Earth's surface (Edenhofer, Pichs-Madruga, Sokona, Seyboth, Eickemeier, Matschoss, Hansen, Kadner, Schlömer, Zwickel & Stechow, 2011). The problem is that these reservoirs are often too deep to exploit and seldom concentrated in terms of location (Barbier, 2002).

When drilling into the Earth, the average increase in temperature is approximately 30 °C/km as you move deeper. This is due to heat from the Earth's core and mantel moving to the surface through various processes including convection and conduction. Locations suitable for geothermal power generation are generally where magma bodies are close to the surface or where geothermal gradients are anomalously high. Sub-surface water reservoirs that were heated by geothermal energy can be accessed when close enough to the surface (Barbier, 2002). When the pressure and temperature of the reservoirs are high enough they can be used for electricity generation.

Geothermal energy can be used for electricity generation or for district and industrial heating. Most power plants use steam condensing turbines to drive generators. Typical plant sizes range from 20 – 110 MW (Edenhofer *et al.*, 2011).

A major advantage of geothermal power is that generation is not dependant on weather or climate conditions and can thus offer a relatively constant power output (Edenhofer *et al.*, 2011), (Tomarov, Nikol'skii, Semenov, Shipkov & Parshin, 2012).

In 2010 the world's installed geothermal power generation capacity exceeded 10 715 MW with a corresponding 67 146 GWh of electricity generated. It was estimated that installed capacity could be as high as 70 GW by 2050 (Tomarov *et al.*, 2012).

Appendix C: System Dynamics

C 1. System dynamics background

System dynamics involves a systems thinking approach. Reality is simplified and approximated to deal with complex problems more effectively. System dynamics models (SDM) resemble reality structurally to aid in reviewing it for usefulness and consistency (Williams & Harris, 2005).

Williams (1999) highlighted the key features and assumptions of system dynamics:

- Most problems have endogenous causes.
- Problem boundary selection is a vital step.
- Only the problem, issue or evaluation questions are modelled, not the real world.
- Events are part of patterns, in turn generated by structures of the system.
- Extent in space and time are more important than details.
- Insights from other models can be incorporated into SDM.

SMD has certain aspects that differentiate it from other modelling methods. These include the following (Williams & Harris, 2005):

- Structures from the real world problem and the model are similar.
- Information feedback is a key focus.
- Quantitative and qualitative aspects can be included in models.
- Hypothesis testing is possible through model simulation.

SDM can simplify and integrate a wide range of aspects of complex problems and is useful for facilitating communication and understanding between different actors (management, scientific and non-scientific actors) and also support the evaluation and analysis of policies (Morecroft, 1988; Musango, 2012). This is especially useful at a municipal level since actors responsible for planning and decision making who come in contact with the model might not have scientific or technical backgrounds.

C 2. System dynamics methodology

Maani and Cavana (2012) describe the five-phased process of systems thinking and modelling as: problem structuring, causal loop modelling, dynamic modelling, scenario planning modelling and finally implementation and organisational learning. The various phases tend to overlap to some degree in the model building progresses, as illustrated in Figure 31.

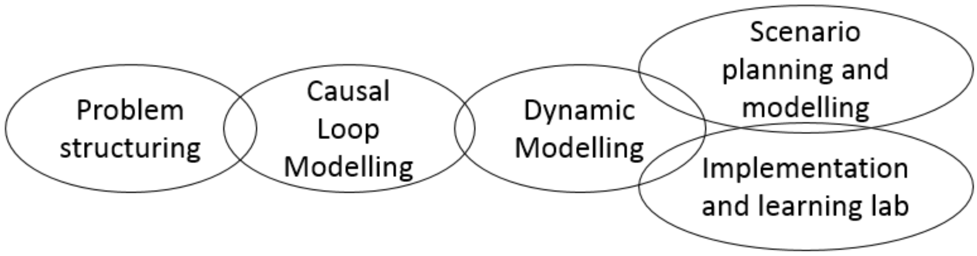

Figure 30: System Dynamics Modelling methodology. Source: Maani and Cavana (2012)

C 3. Causal loop diagrams

Causal loop diagrams (CLD) and stock-and-flow diagrams are tools widely used in system dynamics modelling. Causal loop diagrams mainly focus on the qualitative side of the modelling process and stock-and-flow diagrams are used for quantitative modelling.

System dynamic models usually employ a qualitative approach to understand how different variables in a system are connected or interact before a quantitative model is constructed. Causal loop diagrams are the tools used for this qualitative part of the modelling process. It is important that the causal relationships in these qualitative models are correct. If not, insights or recommendations obtained from the quantitative modelling would be misleading (Qudrat-Ullah, 2012: 160).

The main components of causal loop diagrams are links and variables. Links (or arrows) indicate the causal association between different variable. A variables is defined as a situation, condition, decision or action that can influence other variables or be influenced by them. Variables can be classified into hard (quantitative or measurable) and soft (qualitative) variables. Once the links between different variables have been established, the relationship between variables must further be refined by indicating how one variable impacts another. This is done by marking the link (arrow) heard with either a "+" or "-" sign to respectively indicate a positive or negative correlation between two variables (Maani & Cavana, 2012). These concepts are briefly demonstrated in Figure 32. Population, births and deaths are variables. The links indicate that an increase in population will lead to more births, which in turn will cause an increase in population. This type of cycle is known as a reinforcing loop and is indicated by the "R" symbol in Figure 32. A higher population will also inevitably lead to more deaths. These deaths will decrease the population again, as indicated by the "-" sign forming the link from "Deaths" to "Population". This type of cycle is a balancing cycle, indicated by the "B" in Figure 32.

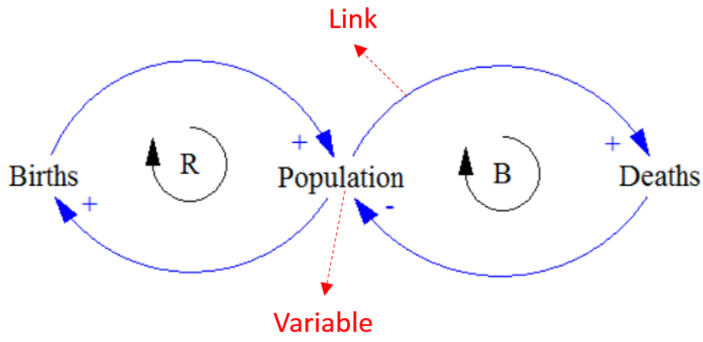

Figure 31: Variables and links in causal loop diagrams

Other CLD concepts that are of significance include Delays. These are indicated by a "||" sign in the links.

C 4. Stock and flow diagrams

Stock and flow diagrams can be constructed after the causal loop modelling has been completed. These diagrams generally contain more details than the causal loop diagrams. The main elements of a stock-and-flow diagram include stocks, flows, auxiliary variables and constants. Stocks are usually represented by blocks. Stocks are things that can accumulate in a system and continue to exist even when all flows in that system stop. Flows connected to stocks and cause changes in stocks during a period of time. Auxiliary variables include graphical or behavioural relationships as well as constants. These are used break down the complexity of some flow equations into simpler, easier to understand, components (Maani & Cavana, 2012). A simple example of a stock and flow diagram, constructed from the CLD in Figure 32 is represented in Figure 33.

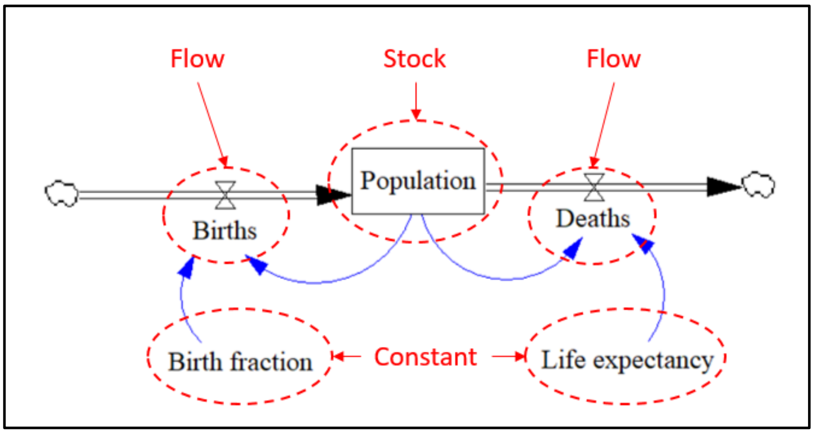

Figure 32: Elements of a stock and flow diagram. Source: Maani and Cavana (2012)

Sterman (2000) discussed the integral and differential equations that govern the behaviour of stocks in a stock and flow model. Equation 99 is used to calculate the value of a stock at time t, and Equation 100 describes the rate of change of a stock.

Equation 99:

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

Equation 100:

$$\frac{dStock(t)}{dt} = Inflow(t) - Outflow(t)$$

Appendix D: Additional Model Information

D 1. Initial Electricity Demand

Eskom does not gather electricity consumption data beyond a district level. Therefore assumptions and approximations had to be made to disaggregate sectoral electricity consumption. Reliable data could only be found for the 2011/2012 year and it is only applicable to Riversdale. The data is presented in Table 34. This data was assumed to be representative of the entire Hessequa municipal area.

Table 34: Electricity demand for Riversdale for 2011/2012. Source: Reinecke and others (*2013)*

Sector		Electricity demand	% of total
		kWh	%
Residential		**18 598 607**	**76.09%**
	Domestic	10 607 658	
	Old age home	414 352	
	Rural	2 741 875	
	Indigents	4 834 722	
Businesses		**5 062 484**	**20.71%**
	Businesses	5 062 484	
Local Government		**780 778**	**3.19%**
	Street Lights	275 184	
	Departmental	505 594	
Total		**24 441 869**	**100.00%**

To estimate 2017's electricity demand for the entire municipal area, the latest available electricity data was used (2016 data) (Hessequa Municipality, 2016). The total demand was split into different sectors, based on the information in Table 34. The results are presented in Table 35.

Table 35: 2017 initial electricity demand estimates

Hessequa Electricity Demand Estimates for 2017		
		kWh
2016 Data		
Total Electricity Demand		87 425 194
2017 Estimates		
Total Electricity Demand		87 425 194
2017 Sector Electricity Demand		
Residential	76.09%	66 524 652
Businesses	20.71%	18 107 807
Local Government	3.19%	2 792 735

D 2. Renewable Energy Technology Learning Curves

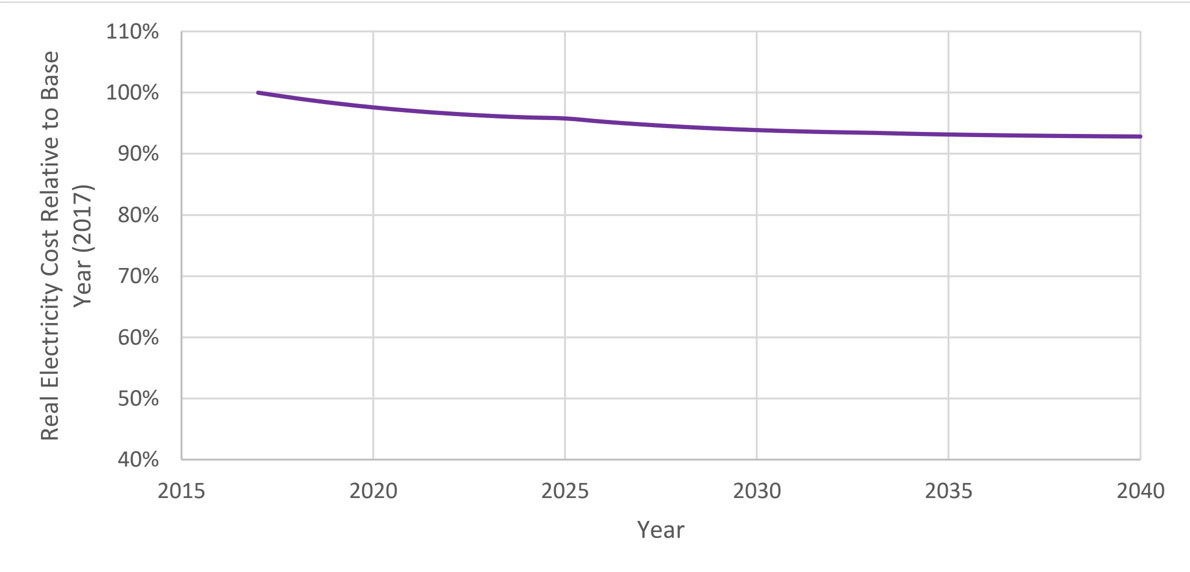

Figure 33: Wind Power Learning Curve

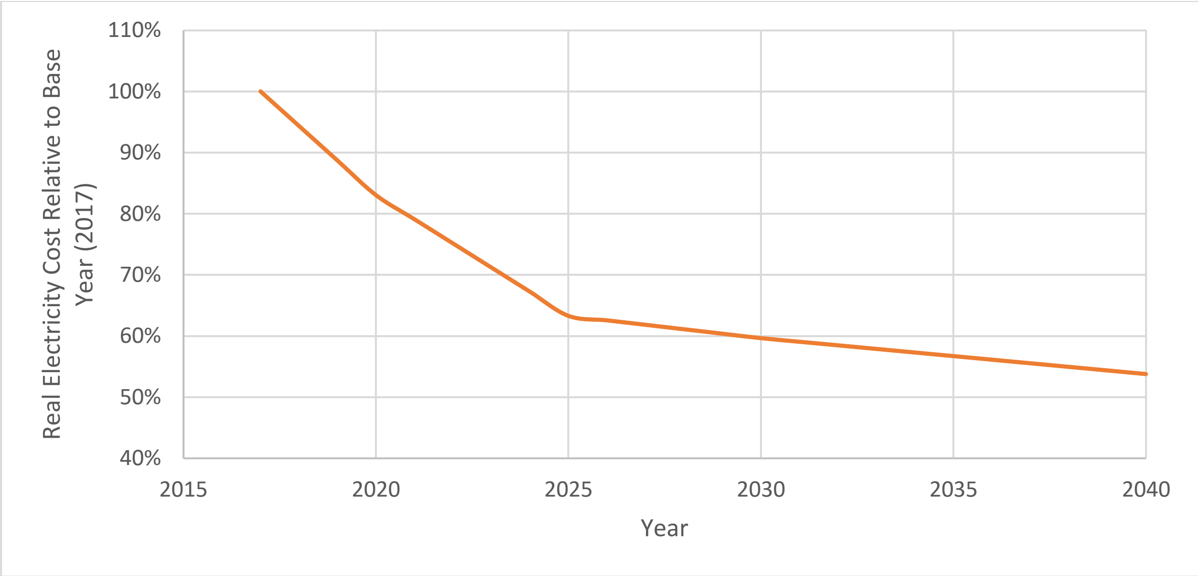

Figure 34: Solar PV Power Learning Curve

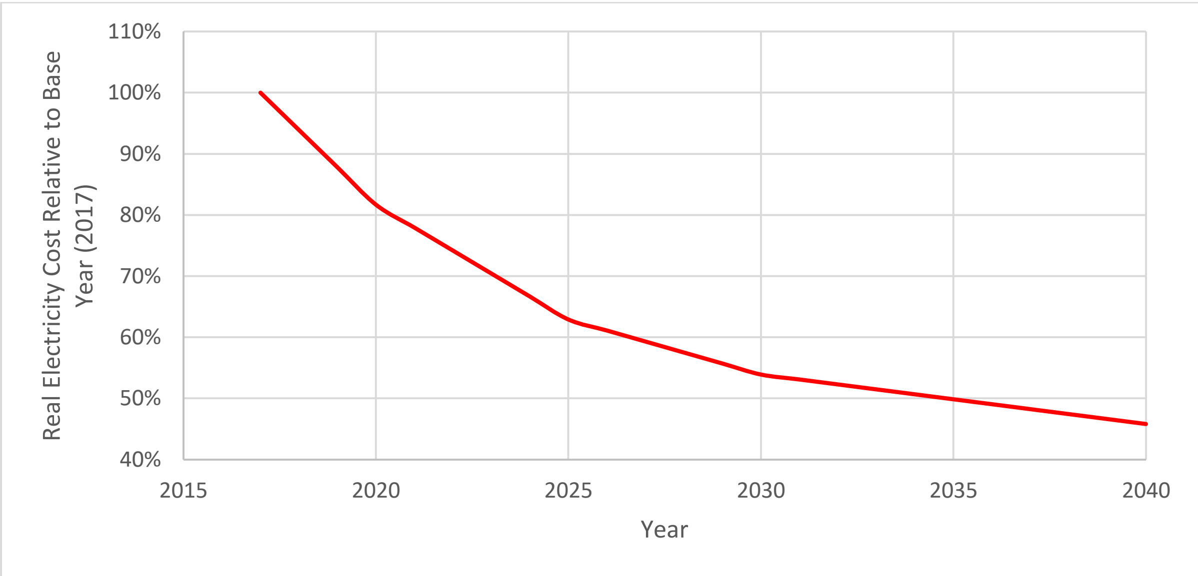

Figure 35: Rooftop PV Learning Curve

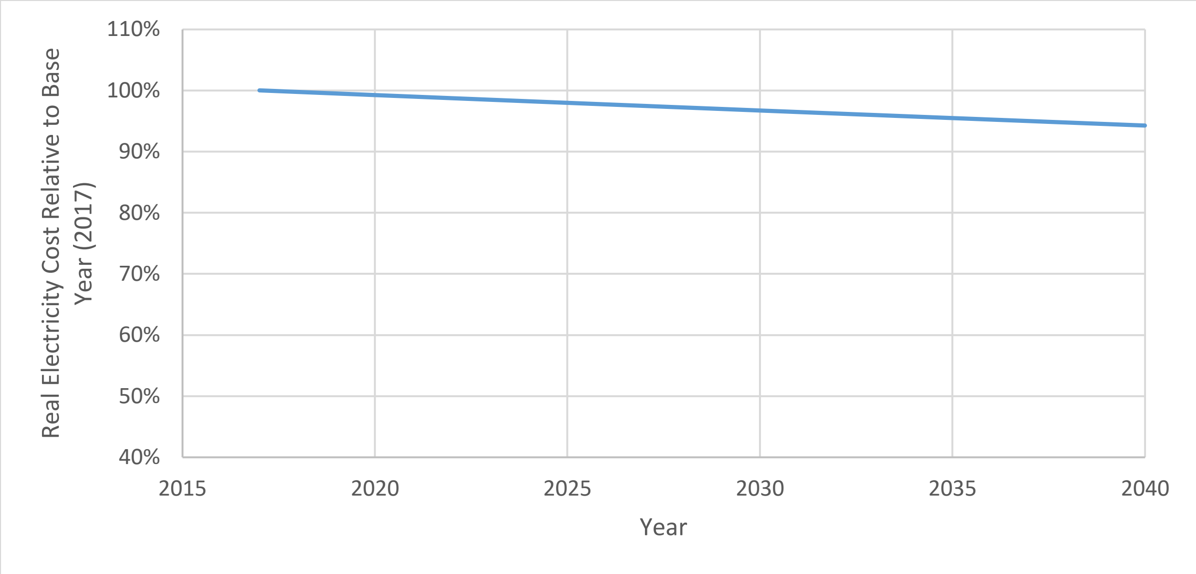

Figure 36: Pumped Storage Learning Curve

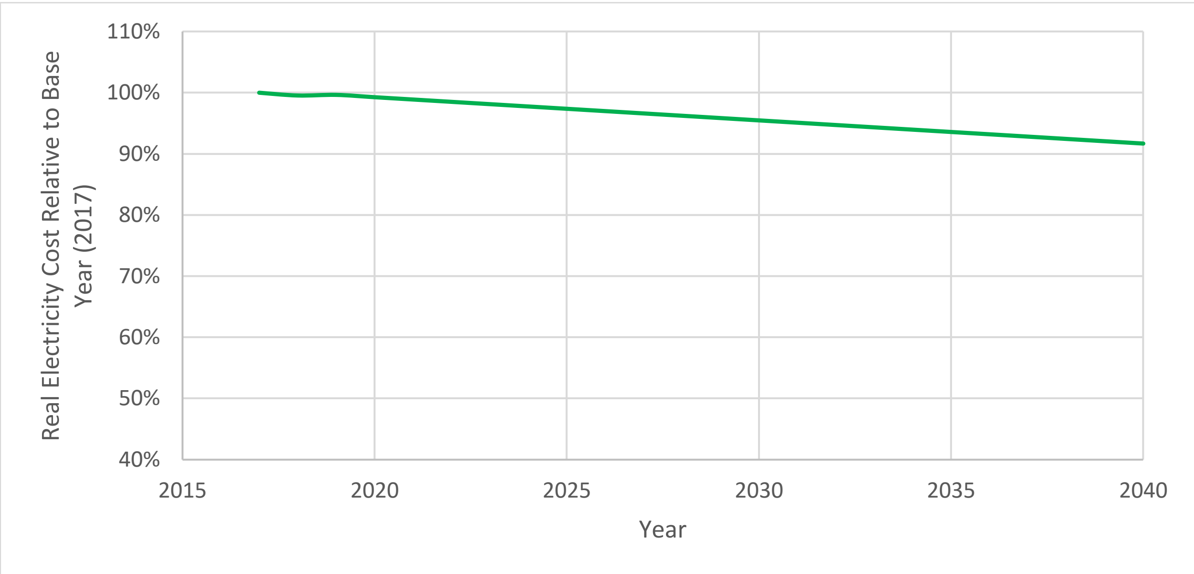

Figure 37: Biomass Power Learning Curve

Appendix E: Hessequa's Renewable Resources

E 1. Introduction

Resource availability will have an impact on the electricity generation potential of the various renewable energy technologies used in the Hessequa are. Due to the nature of system dynamics modelling and the fact that averages will be used in resource potentials, the actual generation potential will vary from the figures reported in the model. An in depth study will be required for solar, wind and biomass resource availability, all of which will have to be site specific for accurate results. Such an in depth study is however beyond the scope of this research.

E 2. Solar resources

Solar resource data was collected using the HelioClim-3 Database. An eleven year average (from 2005 - 2015) was used to minimise annual fluctuations. The possible electricity generation from solar power is limited to when the sun is shining and will be influenced by seasonal changes throughout the year. Figure 39 demonstrates the variation of solar irradiation in Riversdale for the period 2005 – 2015. Figure 39 clearly indicates that winter irradiation levels are more than 50% below summer peaks. These seasonal changes could however not be incorporated into the model. Table 36 presents total annual irradiation of each year at different locations in Hessequa for the period 2005 – 2015. An overall annual average value of 1775 kWh/m^2 per year was used in the model to minimise errors in the predicted electricity generation that might occur due to the location of different solar PV installations. Table 37 presents the exact coordinates of the locations where solar irradiation data was gathered. An optimal fixed tilt angle of 27° was used for the irradiation data.

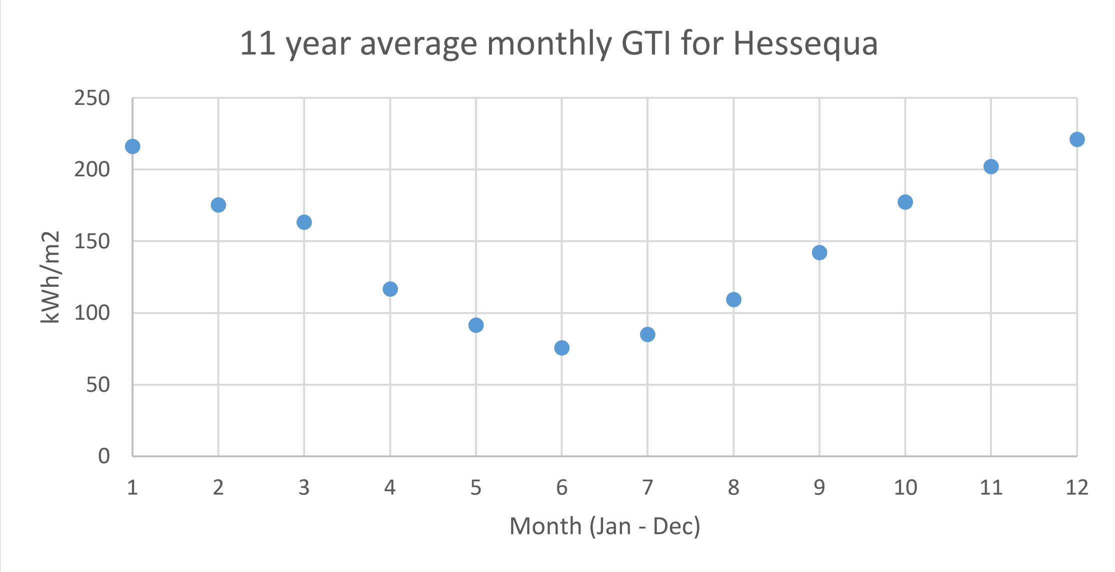

Figure 38: Monthly average Global Tilted Irradiation for Hessequa for the period 2005 - 2015

Table 36: Total annual irradiation in kWh/m^2 for fixed tilt (Data obtained from HelioClim-3 Software)

Town	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	11 year average
Albertinia	1800	1697	1814	1751	1732	1637	1726	1757	1814	1699	1715	**1740**
Gouritsmond	1873	1803	1889	1870	1832	1737	1811	1835	1927	1818	1815	**1837**
Heidelberg	1817	1698	1810	1754	1748	1658	1723	1765	1810	1706	1707	**1745**
Jongensfontein	1853	1756	1862	1838	1795	1697	1758	1812	1863	1785	1773	**1799**
Melkhoutfontein	1801	1698	1809	1774	1736	1636	1716	1758	1810	1713	1712	**1742**
Riversdale	1782	1664	1784	1719	1718	1612	1690	1734	1784	1671	1674	**1712**
Stilbaai	1877	1772	1886	1867	1831	1737	1795	1839	1903	1812	1801	**1829**
Witsand	1856	1757	1864	1832	1788	1711	1746	1808	1836	1787	1772	**1796**
Average annual GTI												**1775**

Table 37: GPS coordinates of locations where solar irradiation data was gathered

Town	Location coordinates	
	S	E
Stilbaai	34^o 22' 54.22''	21^o 24' 39.01''
Albertinia	34^o 12' 25.90''	21^o 35' 32.76''
Riversdale	34^o 05' 58.44''	21^o 15' 15.96''
Gouritsmond	34^o 21' 04.56''	21^o 52' 28.53''
Melkhoutfontein	34^o 19' 21.73''	21^o 25' 21.01''
Jongensfontein	34^o 25' 38.69''	21^o 19' 47.86''
Witsand	34^o 23' 24.26''	20^o 50' 08.08''
Heidelberg	34^o 05' 51.87''	20^o 56' 59.46''

To calculate the potential electricity generation Equation 101 was used (Photovoltaic software, 2016). E is the electricity generated (kWh), A is the solar panel area (m^2), r is the panel efficiency (%), H is the annual solar radiation on the panels (kWh/m^2) and PR is a performance ratio that factors in inverter, temperature, cable and other losses that occur in an average PV system. PR is assumed to be 0.75.

Equation 101

$$E = A \times r \times H \times PR$$

E 3. Wind resources

The Wind Atlas for South Africa was compiled by SANEDI. The goal was to map South Africa's wind resources and develop a Numerical Wind Atlas. The information can be used in large scale utility wind power programmes or off-grid applications (WASA, 2015a). The project covered the Western Cape and partially covered the Eastern and Northern Cape.

Figure 40 illustrates the average wind resources in the Hessequa area. Blue and green colours indicate lower wind speeds. Higher wind speeds are indicated by orange and red. Areas with the highest wind speeds are located close to the coastal and on top of the mountain range. Coastal areas will likely be the better option for wind farms as these area are more easily accessible.

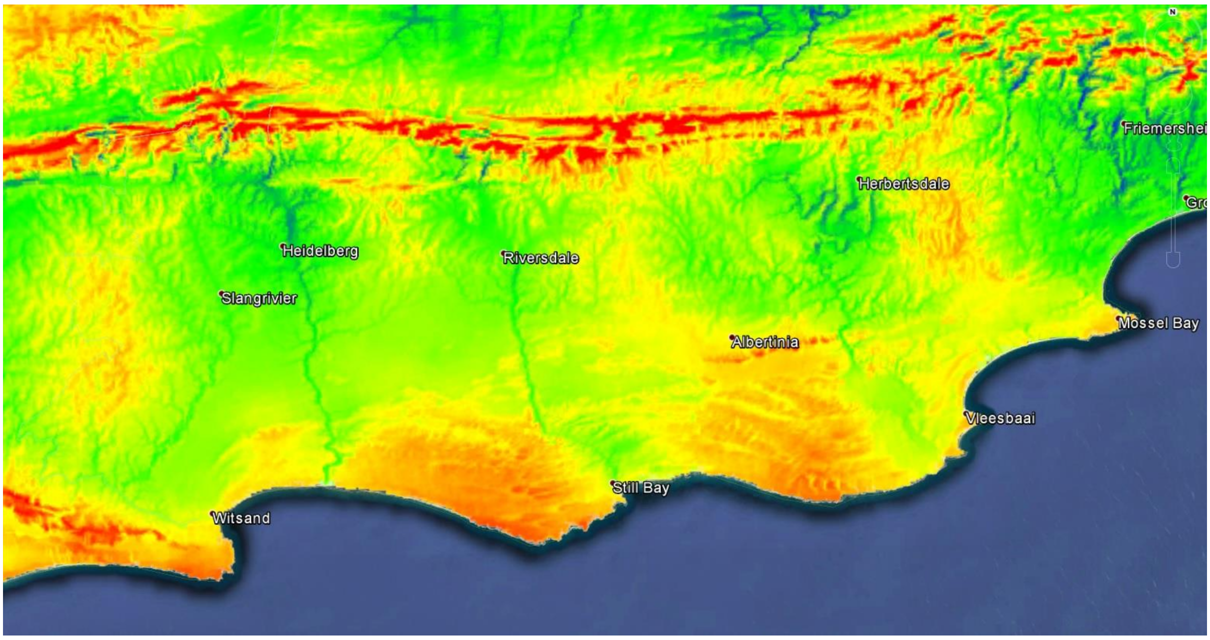

Figure 39: Wind resources for the Hessequa municipal area. Source: WASA (2015b)

Table 38 presents the location, average wind speed and power density of selected sites in Hessequa that might be viable for wind power generation. The wind data was recorded at 100m above ground level.

Table 38: Wind resources of selected sites in the Hessequa municipal area. Source: WASA (2015b, 2016)

Location	Units	R-class 0 (0,000 m)	R-class 3 (0,400 m)	R-class 4 (1,500 m)
Albertinia area				
34.219S_21.642E	m/s	8,45	6,25	5,28
	W/m^2	798	300	183
34.241S_21.546E	m/s	7,70	5,89	4,90
	W/m^2	678	253	155
Stilbaai - Jongensfontein Area				
34.394S_21.255E	m/s	8,59	6,43	5,36
	W/m^2	849	318	194
34.387S_21.287E	m/s	8,67	6,52	5,47
	W/m^2	835	316	192
Stilbaai - Gouritsmond Area				
34.358S_21.655E	m/s	8,60	6,46	5,43
	W/m^2	884	330	202
34.384S_21.664E	m/s	8,42	6,18	5,21
	W/m^2	799	300	184

E 4. Biomass resources

Accurate and reliable information regarding the availability of biomass resources, especially invasive alien plants is difficult to obtain. This is regarded by many in the industry as a major obstacle in utilising such resources. In 2017 the South African Bio-energy Atlas was launched. It will serve as a source of information for processes of biomass energy production and the environmental, social and economic impacts these value chains will have (SAEON, 2016). Information from the bio-energy atlas will be used as this seems to be the only reliable quantitative source of information on the availability of biomass in the Hessequa area.

CSIR (2011) created a mesozone grid for the whole South Africa to assist with spatial socio-economic data analysis. Each mesozone has an area of approximately 50 km^2. Figure 41 illustrates the results of the bio-energy atlas study and the availability of invasive alien plants in the Hessequa area. The mesozone grid created by the CSIR was used here as well. The availability was based on the exploitable species, typical mass of these species and the ease of exploitation. It was assumed that the invasive species would be eradicated in a 20 year period. The availability is thus based on the assumption that 1/20 of the biomass will be harvested each year. New biomass growth has been accounted for in the availability estimates. Should the alien plants be successfully eradicated within the proposed time frame, it will have a negative impact on the availability of woody biomass. An alternative biomass resource like short rotation coppicing stands (eucalyptus species) or indigenous woody biomass would then have to be utilised (SAEON, 2016). Neither of these scenarios would be ideal as indigenous trees grow relatively slowly and an incentive would be created to plant more non-indigenous or invasive alien plants instead of eradicating them.

Based on the information in Figure 41, the area between Albertinia and Stilbaai has the largest concentration of exploitable biomass (see Figures 41, 42 and 43 and Table 39, 40, 41, 42 and 43). According to the bioenergy atlas estimates, the mesozones that offer the highest exploitability of IAPs in Hessequa can have a combined yield ranging from 97 536 - 220 498 t/year over a 20 year period. Assuming a Johansson biomass gasifier and generator as described by Nwokolo, Mamphweli, Meyer and Tangwe (2014) is used for converting biomass to electricity, the biomass from these areas have the potential to generate approximately 90 731.15 – 205 114.57 MWh/year. This minimum scenario (90 731.15 MWh/year) is more than what Hessequa purchased from Eskom (85 252.75 MWh) for the financial year 2014/2015 (Hessequa Municipality, 2015). The total exploitable invasive alien biomass in Hessequa was estimated between 142 475.69 – 449 179.55 t/year. It should however be noted that the study conducted by Nwokolo and others (2014) used pine wood with a calorific value of 16.34 MJ/kg. The calorific value of invasive species biomass assumed in the Bioenergy Atlas was 14.7 MJ/kg (Hugo, 2017). There will thus be some variation in the actual electricity generating potential of the IAPs found in Hessequa. It should also be noted that the majority of IAPs in the area under consideration is Acacia cyclops (see Figure 42 and Figure 43).

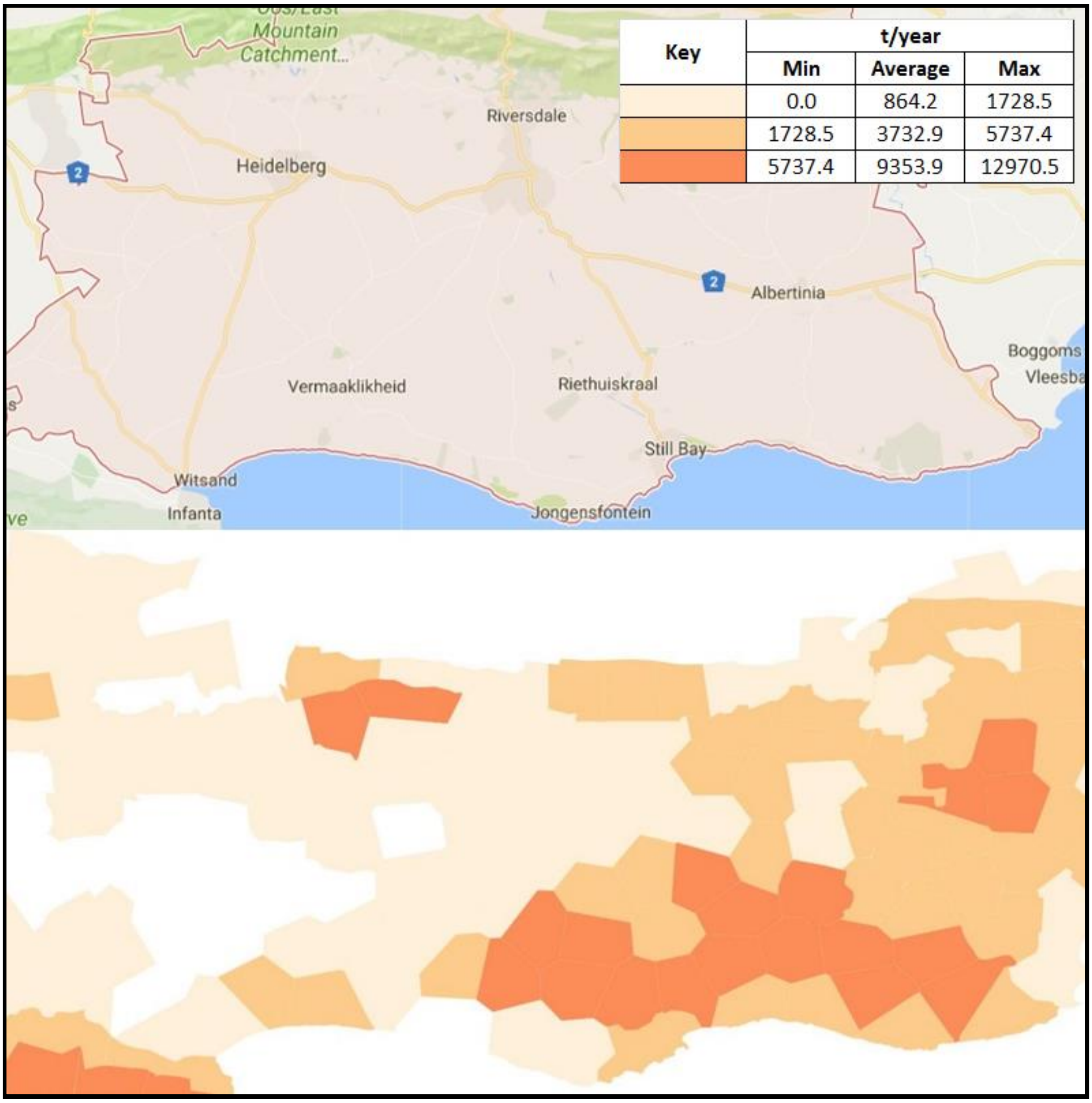

Figure 40: Exploitable invasive alien biomass in the Hessequa municipal area. Source: SAEON (2015)

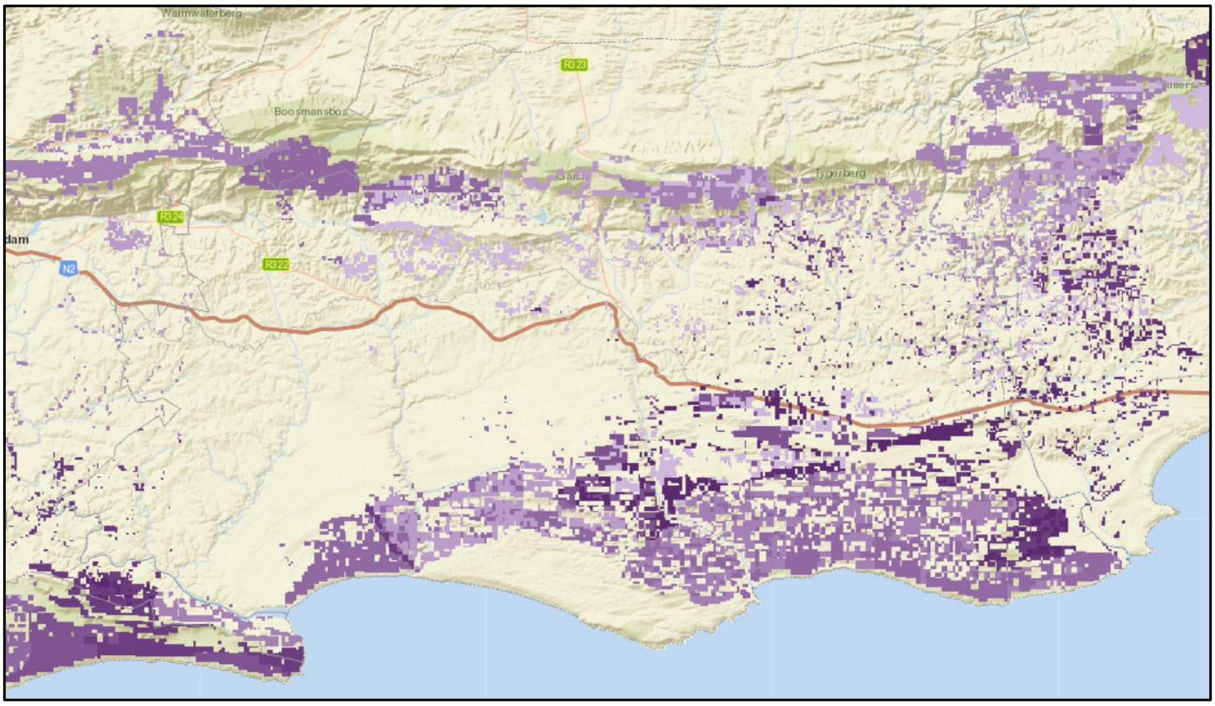

Figure 41: Cover of major IAP species present in Hessequa. Source: SANBI (2010a)

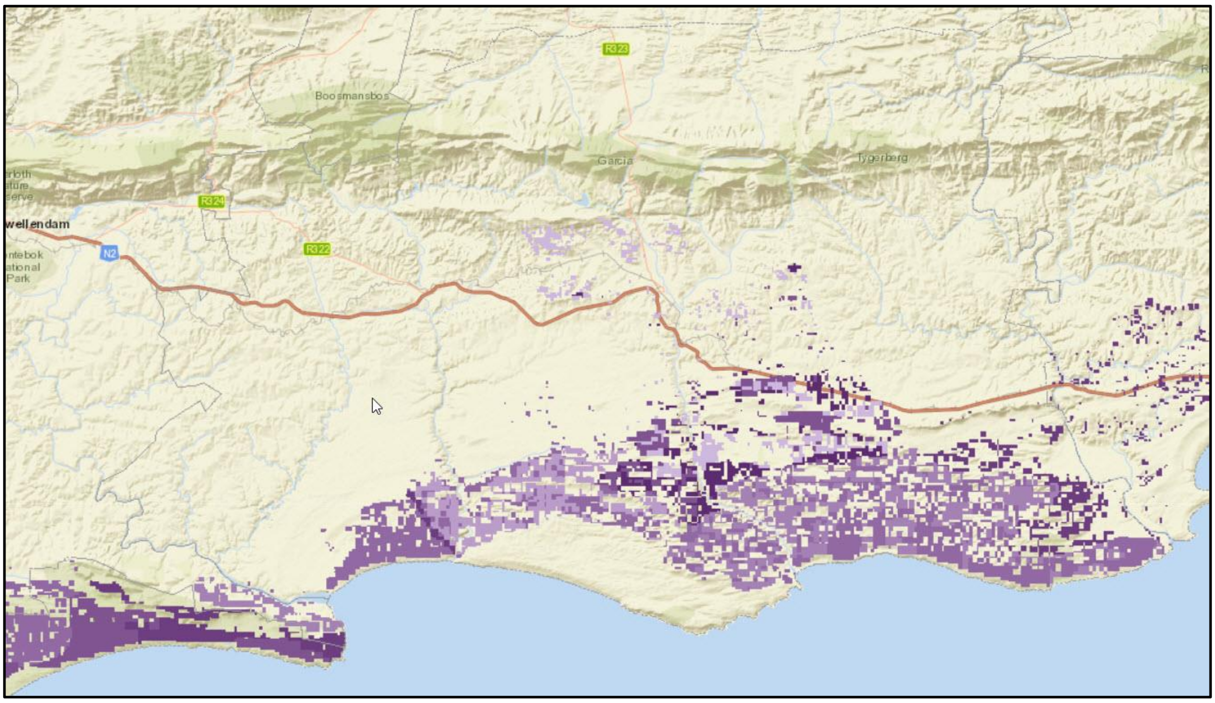

Figure 42: Acacia cyclops cover in Hessequa. Source: SANBI (2010a)

It is considered unrealistic to assume that all invasive alien biomass in Hessequa will be eradicated in a 20 year period, as is assumed in the BioEnergy Atlas. This factor would also limit the potential life of biomass power plants if alternative fuel sources are not used. Instead, the BioEnergy Atlas' estimates are used as a starting point. In reality, the feedstock will most likely grow faster than it is being harvested for power generation purposes. Without large scale clearing efforts IAPs are also likely to remain prevalent in the area. The following process is used to estimate the IAP biomass stock:

- Only the mesozones with the highest concentration of IAPs are considered as viable sources of biomass fuel (5 737.41 – 12 970.48 t/year). This will limit labour and transport costs to some degree.
- A mean exploitable biomass value of 9 353.95 t/year is used for these mesozones. The total annual exploitable biomass is then multiplied by 20 (as the BioEnergy Atlas estimates were for a 20 year period). This amounts to an estimated biomass stock of 3 180 341.76 t that could potentially be used for biomass power generation. This is used as the biomass feedstock in the model ($Biomass_{Feedstock}$).
- In the model this bulked value was assumed to be the initial value of the stock and will be depleted based on biomass resource requirements of the proposed biomass power generation technologies that are implemented over the modelling period.

A more complex approach should be followed in a feasibility study (preferably by an IPP) where regrowth rates, transport cost and transport distances are also considered. Such a detailed analysis is however beyond the scope of this work.

The model assumes the fuel requirements of the Johansson Biomass Gasifier (1.075 kg fuel/kWh) as described by Nwokolo and others (2014) for biomass power generation. The annual biomass fuel demand ($Fuel\ Demand_{Biomass}$) is calculated by multiplying the electricity generation from biomass ($EG_{Biomass}$) with the fuel demand per MWh of electricity generation ($Fuel\ Demand_{Biomass\ per\ MWh}$) (see Equation 102).

Equation 102

$$Fuel\ Demand_{Biomass}(t) = EG_{Biomass}(t) \times Fuel\ Demand_{Biomass\ per\ MWh}$$

It is then assumed that biomass would be harvested each year equivalent to the annual biomass fuel demand, which was used as a harvest rate ($Harvesting$). The harvest rate is then used as the rate at which the primary biomass fuel resources become depleted (see Equation 103). The cumulative harvested biomass ($Biomass_{Harvested}$) is also calculated (see Equation 104).

Equation 103

$$Biomass_{Feedstock}(t) = \int_{t_0}^{t} [-Harvesting(s)]ds + Biomass_{Feedstock}(t_0)$$

Equation 104

$$Biomass_{Harvested}(t) = \int_{t_0}^{t} [Harvesting(s)]ds + Biomass_{Harvested}(t_0)$$

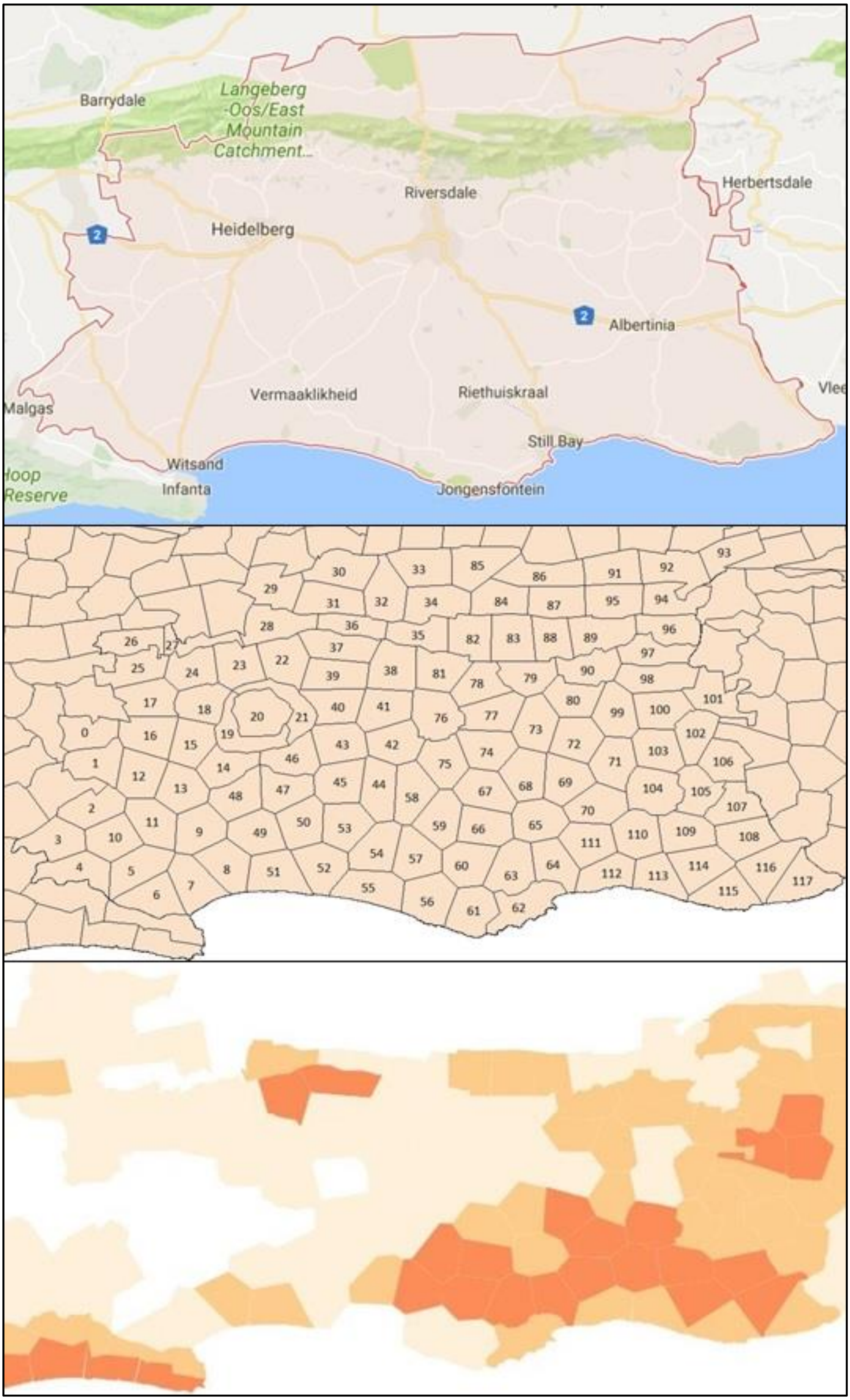

Figure 43: Exploitable invasive alien plant biomass in Hessequa. Source: SAEON (2015)

Table 39: Mesozone biomass availability

Code	Exploitable invasive alien biomass		
	Min	Mean	Max
	t/year	t/year	t/year
0	0	0	0
1	0	864.23	1728.45
2	1728.45	3732.93	5737.41
3	5737.41	9353.95	12970.48

Table 40: High biomass yield mesozones

	Mesozone number	Code	Exploitable Invasive alien biomass		
			Min	Mean	Max
			t/year	t/year	t/year
1	22	3	5737.41	9353.95	12970.48
2	37	3	5737.41	9353.95	12970.48
3	57	3	5737.41	9353.95	12970.48
4	59	3	5737.41	9353.95	12970.48
5	60	3	5737.41	9353.95	12970.48
6	63	3	5737.41	9353.95	12970.48
7	64	3	5737.41	9353.95	12970.48
8	66	3	5737.41	9353.95	12970.48
9	69	3	5737.41	9353.95	12970.48
10	70	3	5737.41	9353.95	12970.48
11	104	3	5737.41	9353.95	12970.48
12	108	3	5737.41	9353.95	12970.48
13	109	3	5737.41	9353.95	12970.48
14	110	3	5737.41	9353.95	12970.48
15	111	3	5737.41	9353.95	12970.48
16	114	3	5737.41	9353.95	12970.48
17	116	3	5737.41	9353.95	12970.48
Total			**97535.99**	**159017.09**	**220498.16**

Table 41: Medium biomass yield mesozones

	Mesozone number	Code	Exploitable Invasive alien biomass		
			Min	Mean	Max
			t/year	t/year	t/year
1	8	2	1728.45	3732.93	5737.41
2	28	2	1728.45	3732.93	5737.41
3	51	2	1728.45	3732.93	5737.41
4	54	2	1728.45	3732.93	5737.41
5	62	2	1728.45	3732.93	5737.41
6	65	2	1728.45	3732.93	5737.41
7	67	2	1728.45	3732.93	5737.41
8	68	2	1728.45	3732.93	5737.41
9	71	2	1728.45	3732.93	5737.41
10	80	2	1728.45	3732.93	5737.41
11	82	2	1728.45	3732.93	5737.41
12	83	2	1728.45	3732.93	5737.41
13	88	2	1728.45	3732.93	5737.41
14	90	2	1728.45	3732.93	5737.41
15	97	2	1728.45	3732.93	5737.41
16	98	2	1728.45	3732.93	5737.41
17	99	2	1728.45	3732.93	5737.41
18	101	2	1728.45	3732.93	5737.41
19	102	2	1728.45	3732.93	5737.41
20	105	2	1728.45	3732.93	5737.41
21	106	2	1728.45	3732.93	5737.41
22	107	2	1728.45	3732.93	5737.41
23	112	2	1728.45	3732.93	5737.41
24	113	2	1728.45	3732.93	5737.41
25	115	2	1728.45	3732.93	5737.41
26	117	2	1728.45	3732.93	5737.41
Total			**44939.70**	**97056.20**	**149172.69**

Table 42: Low biomass yield mesozones – part 1

	Mesozone number	Code	Exploitable Invasive alien biomass		
			Min	Mean	Max
			t/year	t/year	t/year
1	0	1	0.00	864.23	1728.45
2	2	1	0.00	864.23	1728.45
3	3	1	0.00	864.23	1728.45
4	4	1	0.00	864.23	1728.45
5	6	1	0.00	864.23	1728.45
6	7	1	0.00	864.23	1728.45
7	10	1	0.00	864.23	1728.45
8	17	1	0.00	864.23	1728.45
9	18	1	0.00	864.23	1728.45
10	19	1	0.00	864.23	1728.45
11	20	1	0.00	864.23	1728.45
12	21	1	0.00	864.23	1728.45
13	23	1	0.00	864.23	1728.45
14	24	1	0.00	864.23	1728.45
15	25	1	0.00	864.23	1728.45
16	35	1	0.00	864.23	1728.45
17	36	1	0.00	864.23	1728.45
18	38	1	0.00	864.23	1728.45
19	39	1	0.00	864.23	1728.45
20	40	1	0.00	864.23	1728.45
21	41	1	0.00	864.23	1728.45
22	42	1	0.00	864.23	1728.45
23	44	1	0.00	864.23	1728.45
24	45	1	0.00	864.23	1728.45
25	46	1	0.00	864.23	1728.45
26	49	1	0.00	864.23	1728.45
27	50	1	0.00	864.23	1728.45
28	52	1	0.00	864.23	1728.45
29	53	1	0.00	864.23	1728.45
30	56	1	0.00	864.23	1728.45
31	58	1	0.00	864.23	1728.45
32	61	1	0.00	864.23	1728.45
33	72	1	0.00	864.23	1728.45
34	73	1	0.00	864.23	1728.45
35	74	1	0.00	864.23	1728.45
36	75	1	0.00	864.23	1728.45
37	76	1	0.00	864.23	1728.45
38	77	1	0.00	864.23	1728.45
39	78	1	0.00	864.23	1728.45
40	79	1	0.00	864.23	1728.45
41	81	1	0.00	864.23	1728.45

Table 43: Low biomass yield mesozones – part 2

	Mesozone number	Code	Exploitable Invasive alien biomass		
			Min	Mean	Max
			t/year	t/year	t/year
Continued from Table 42					
42	89	1	0.00	864.23	1728.45
43	94	1	0.00	864.23	1728.45
44	96	1	0.00	864.23	1728.45
45	100	1	0.00	864.23	1728.45
46	103	1	0.00	864.23	1728.45
Total			**0.00**	**39754.35**	**79508.70**

Table 44: Total exploitable IAP biomass in Hessequa

Zones	Code	Exploitable Invasive alien biomass		
		Min	Mean	Max
		t/year	t/year	t/year
High yield zones	3	97535.99	159017.09	220498.16
Medium yield zones	2	44939.70	97056.20	149172.69
Low yield zones	1	0.00	39754.35	79508.70
Total yield		**142475.69**	**295827.64**	**449179.55**

Appendix F: Hessequa's Electricity Demand History

Table 45: Hessequa's annual electricity demand history. Source: Lesch (2017b)

Year	Witsand	Heidelberg	Diepkloof	Jongens-fontein	Gouritz-mond	Melkhout-fontein	Riversdale	Stilbaai	Albertinia	Total	Change
	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	%
2003	2 719 178	10 677 066	1 054 545	2 072 884	1 859 662	1 468 541	26 641 205	16 671 185	6 766 498	69 930 765	
2004	2 928 947	11 139 749	1 229 295	2 124 771	1 928 759	1 591 852	27 555 136	17 446 580	7 054 818	72 999 907	4.39%
2005	3 151 984	11 403 216	1 324 925	1 905 944	1 990 578	1 670 164	28 937 587	19 496 729	7 351 625	77 232 752	5.80%
2006	3 315 569	12 031 443	1 448 961	2 294 196	2 079 324	1 734 724	29 457 756	20 236 588	7 803 635	80 402 196	4.10%
2007	3 456 904	12 318 884	1 524 386	2 460 549	2 116 956	1 774 412	31 581 074	21 069 105	8 272 485	84 574 755	5.19%
2008	3 356 955	12 307 106	1 600 598	2 558 233	2 104 959	1 819 838	32 812 184	21 035 507	8 556 019	86 151 399	1.86%
2009	3 471 061	12 126 701	1 640 077	2 569 973	2 070 826	1 918 773	33 689 976	21 381 744	8 567 414	87 436 545	1.49%
2010	3 461 874	12 104 085	1 685 327	2 516 866	2 080 973	1 994 674	32 277 885	20 826 440	8 967 380	85 915 504	-1.74%
2011	3 345 700	12 012 676	1 680 086	2 494 368	2 031 471	1 986 201	32 753 562	20 558 932	9 251 692	86 114 688	0.23%
2012	3 280 038	12 299 804	1 501 245	2 445 669	1 917 128	1 551 497	32 553 197	20 408 138	9 491 533	85 448 249	-0.77%
2013	3 202 151	12 102 208	2 092 787	2 418 507	1 877 905	809 779	32 937 453	20 805 882	9 239 256	85 485 928	0.04%
2014	3 137 946	12 316 694	1 724 109	2 431 572	1 808 966	881 036	32 770 009	20 845 877	9 594 882	85 511 091	0.03%
2015	2 981 459	11 809 036	2 221 327	2 429 486	1 861 249	927 369	33 064 513	20 609 014	9 758 075	85 661 528	0.18%

Appendix G: Model Testing Results

G 1. Extreme condition test results

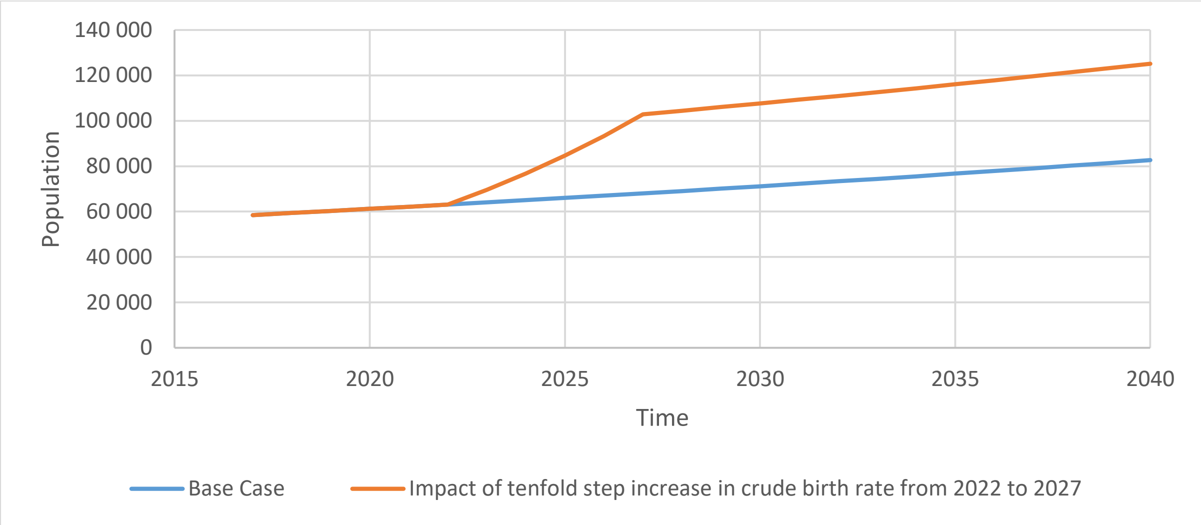

Figure 44: Extreme Condition Test 1: Tenfold step increase in crude birth rate

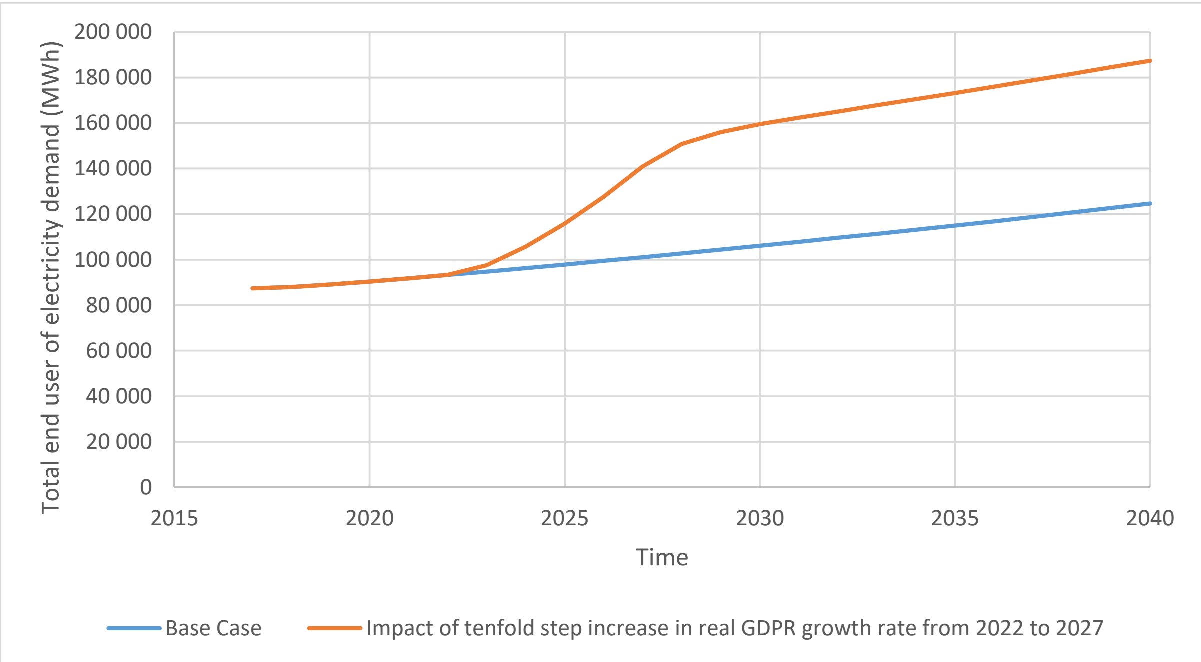

Figure 45: Extreme Condition Test 2: Tenfold step increase in real GDPR growth rate

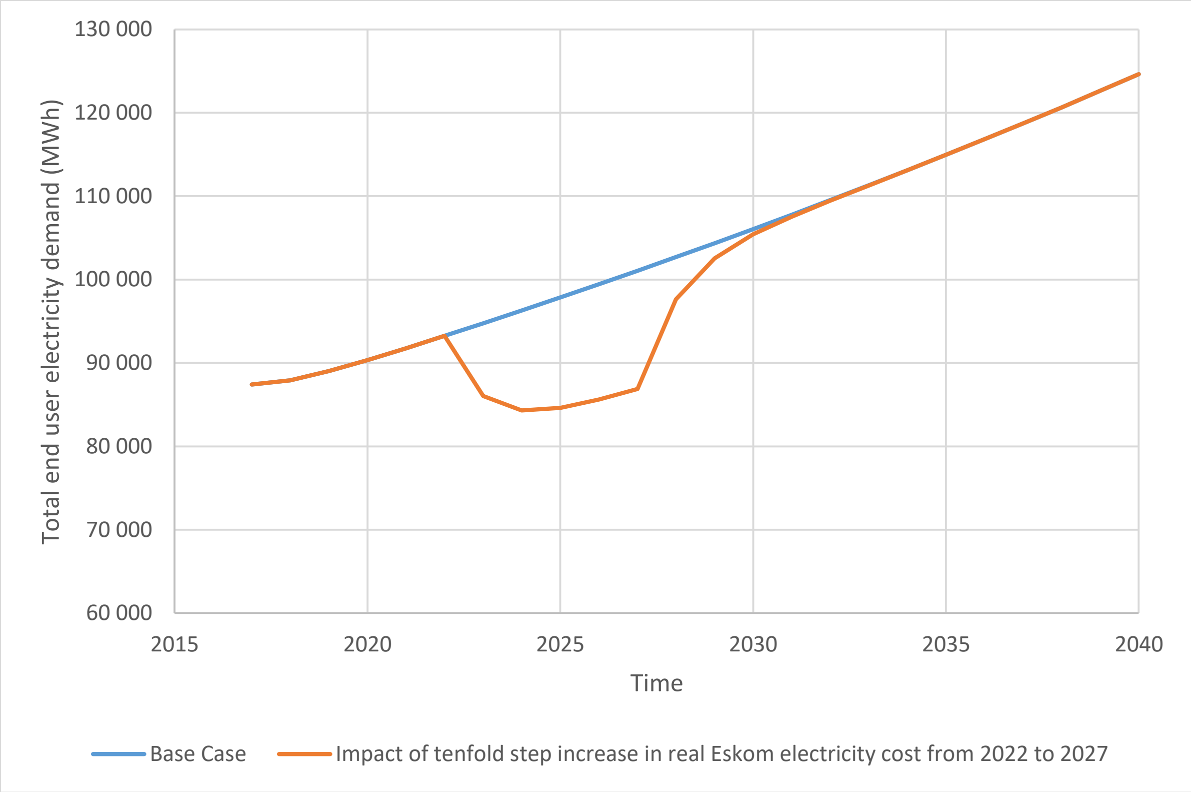

Figure 46: Extreme Condition Test 3: Tenfold step increase in real Eskom electricity cost

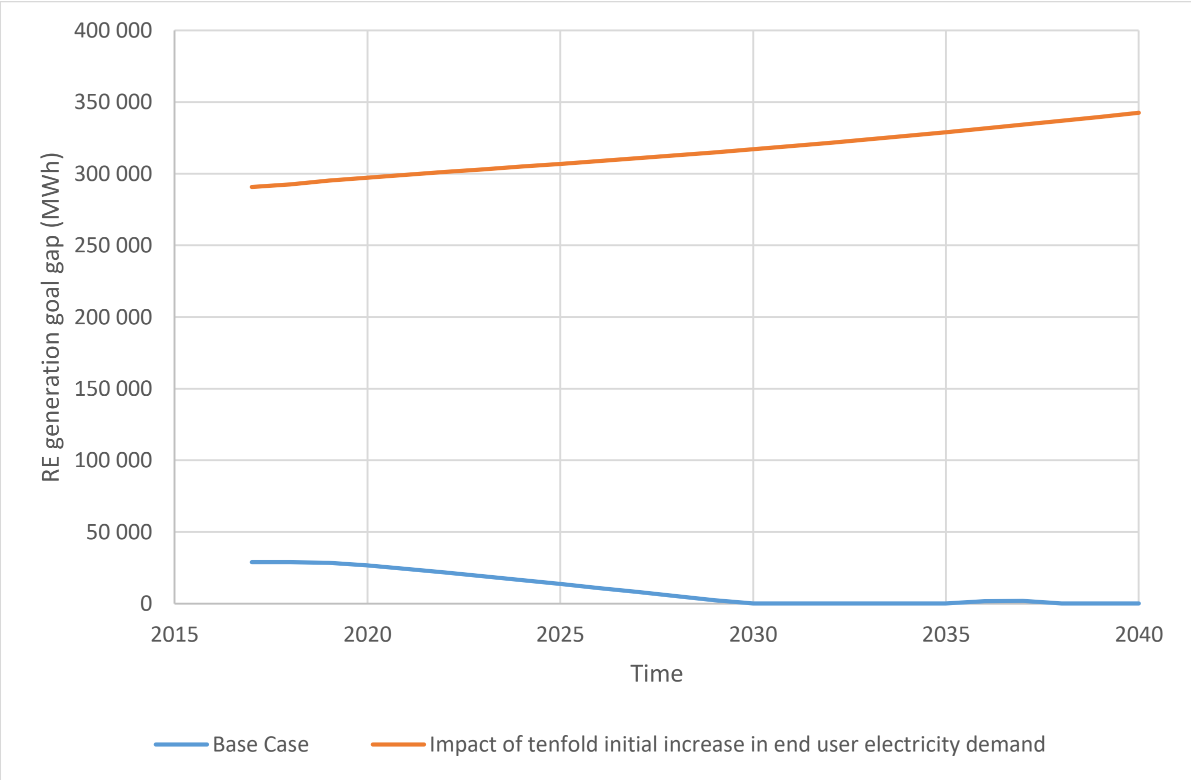

Figure 47: Extreme Condition Test 4: Tenfold increase in initial end user electricity demand

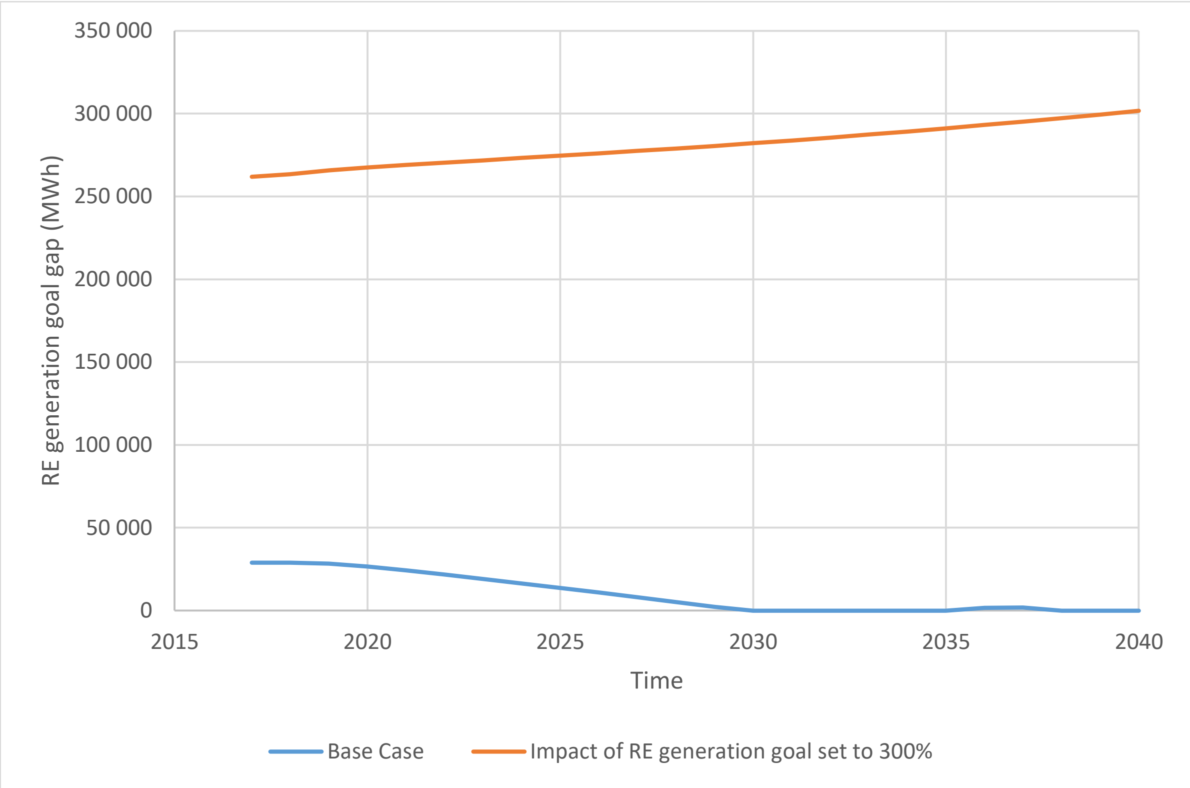

Figure 48: Extreme Condition Test 5: Renewable energy generation goal set to 300%

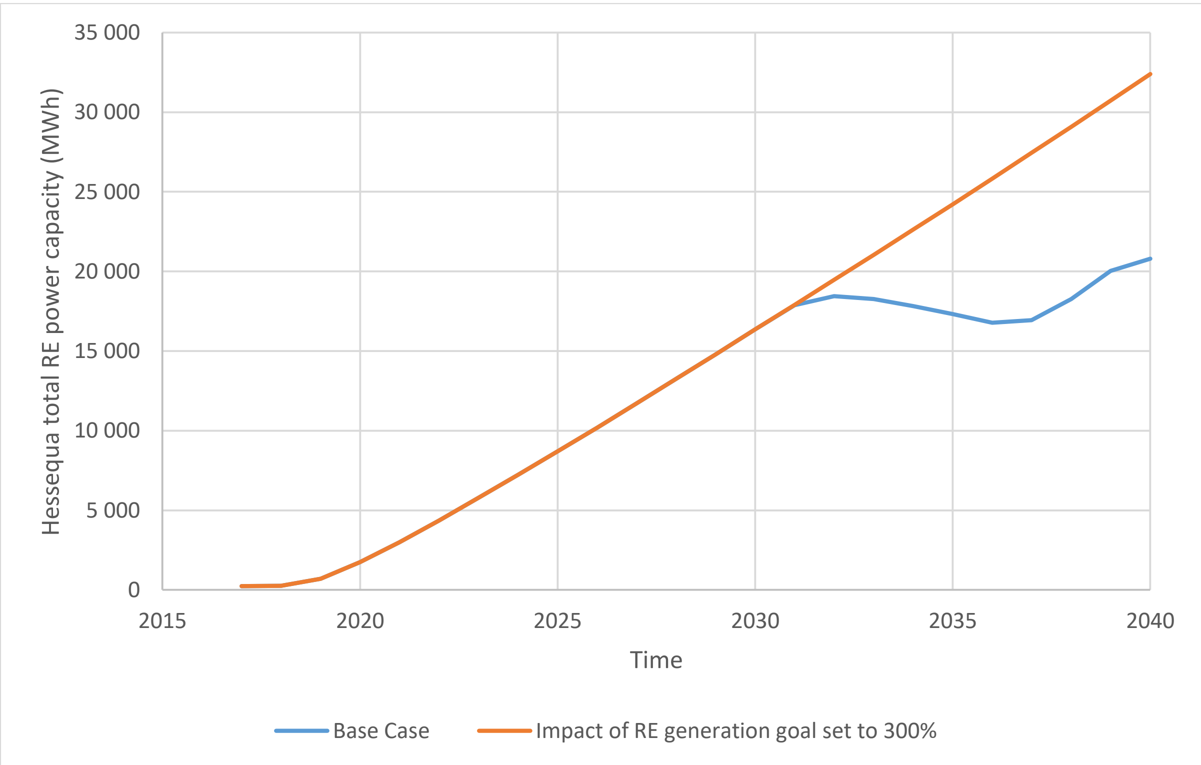

Figure 49: Extreme Condition Test 6: Renewable energy generation goal set to 300%

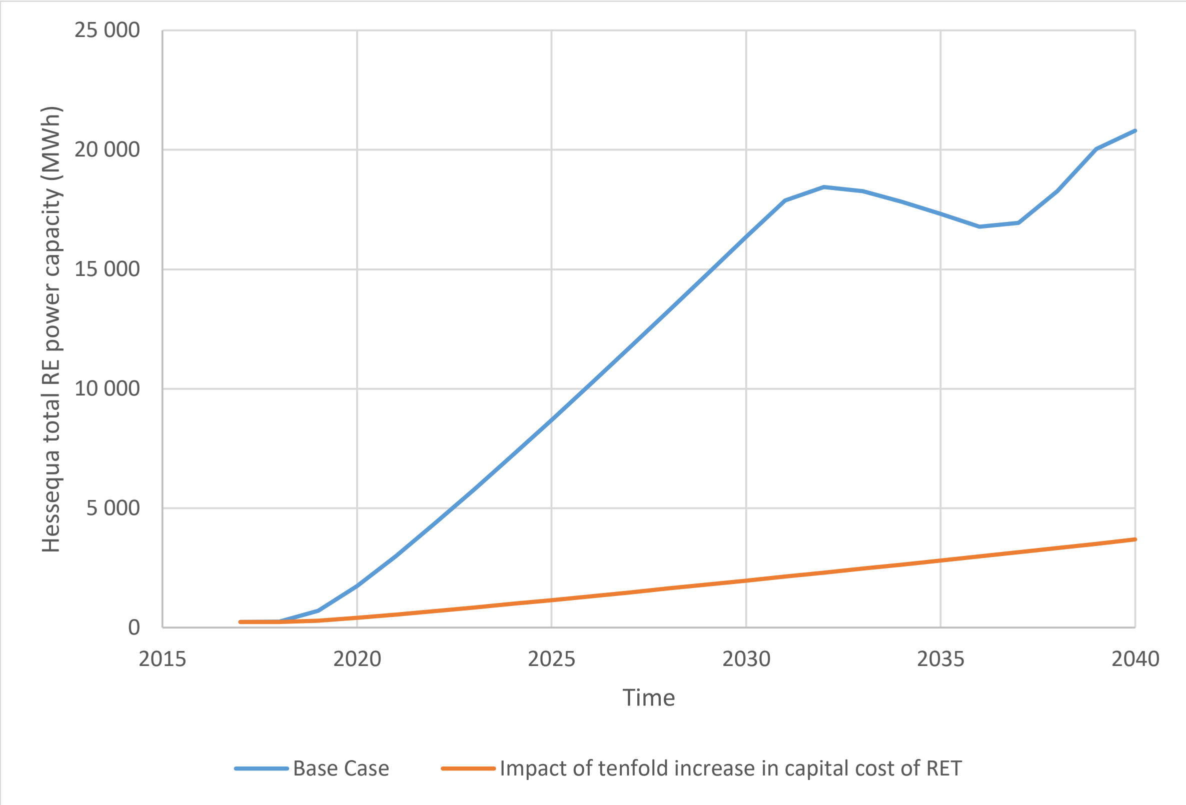

Figure 50: Extreme Condition Test 7: Tenfold initial increase in capital cost of generation capacity

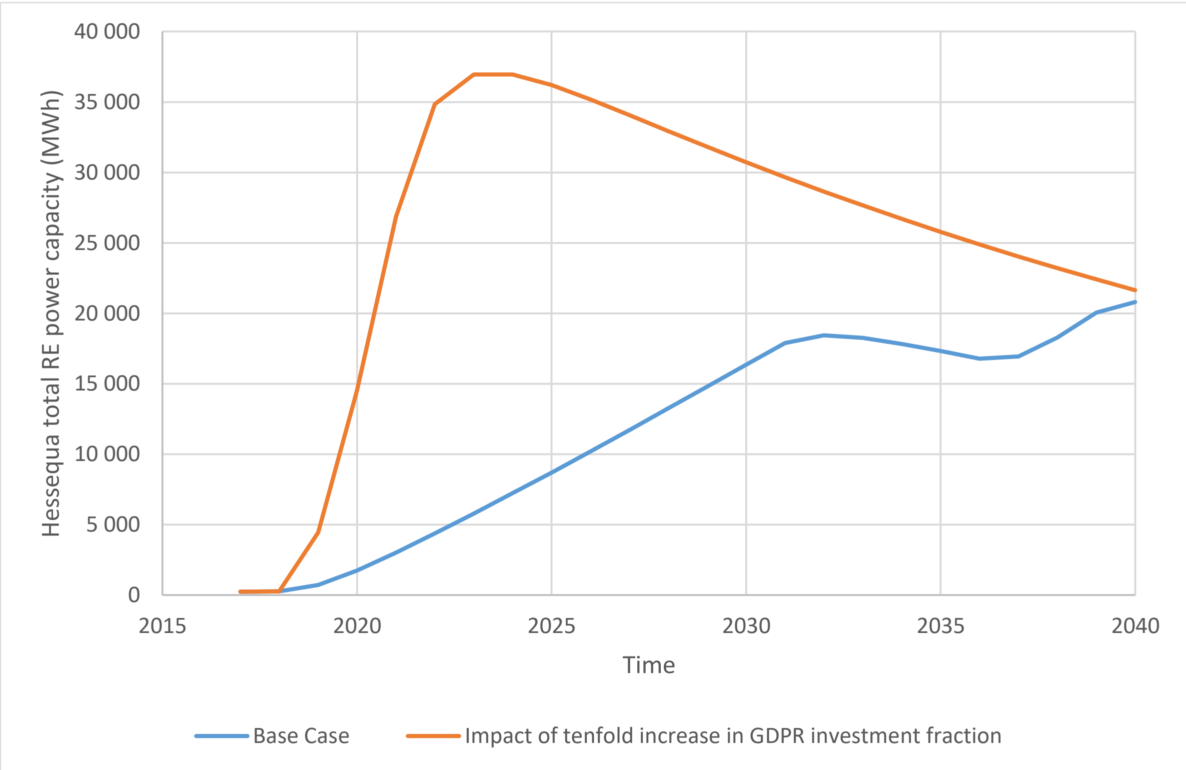

Figure 51: Extreme Condition Test 8: Tenfold initial increase in GDPR investment fraction

G 2. Behaviour anomaly test results

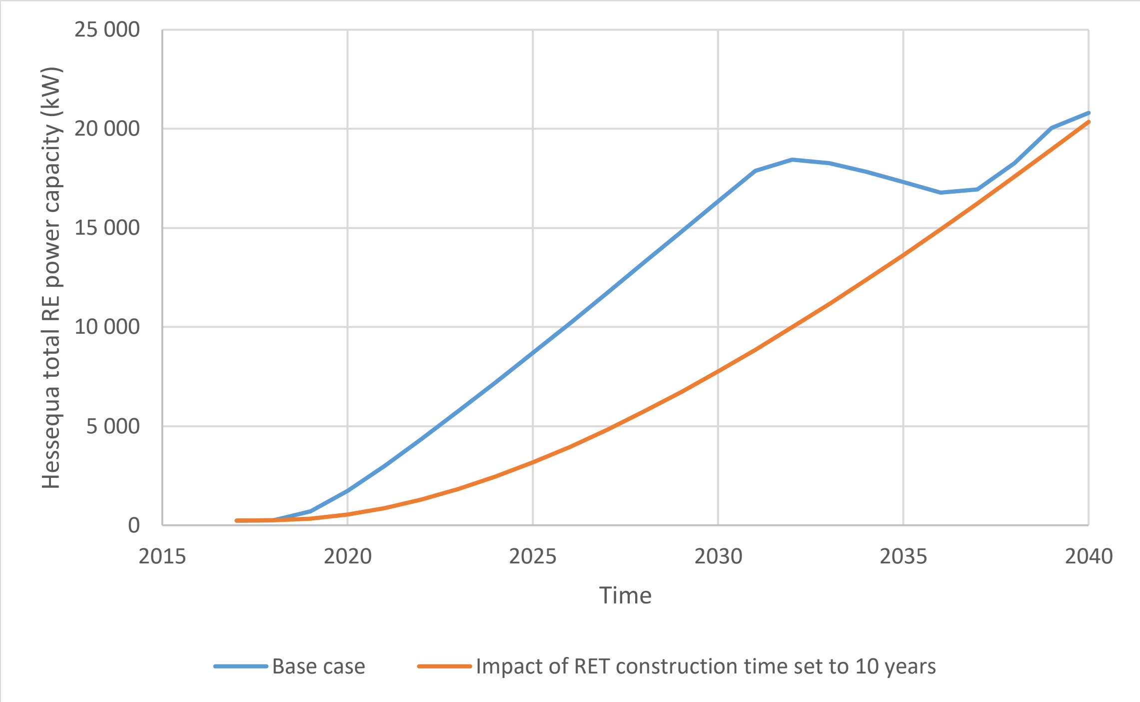

Figure 52: Behaviour Anomaly Test 1: Impact of RET construction time set to 10 years

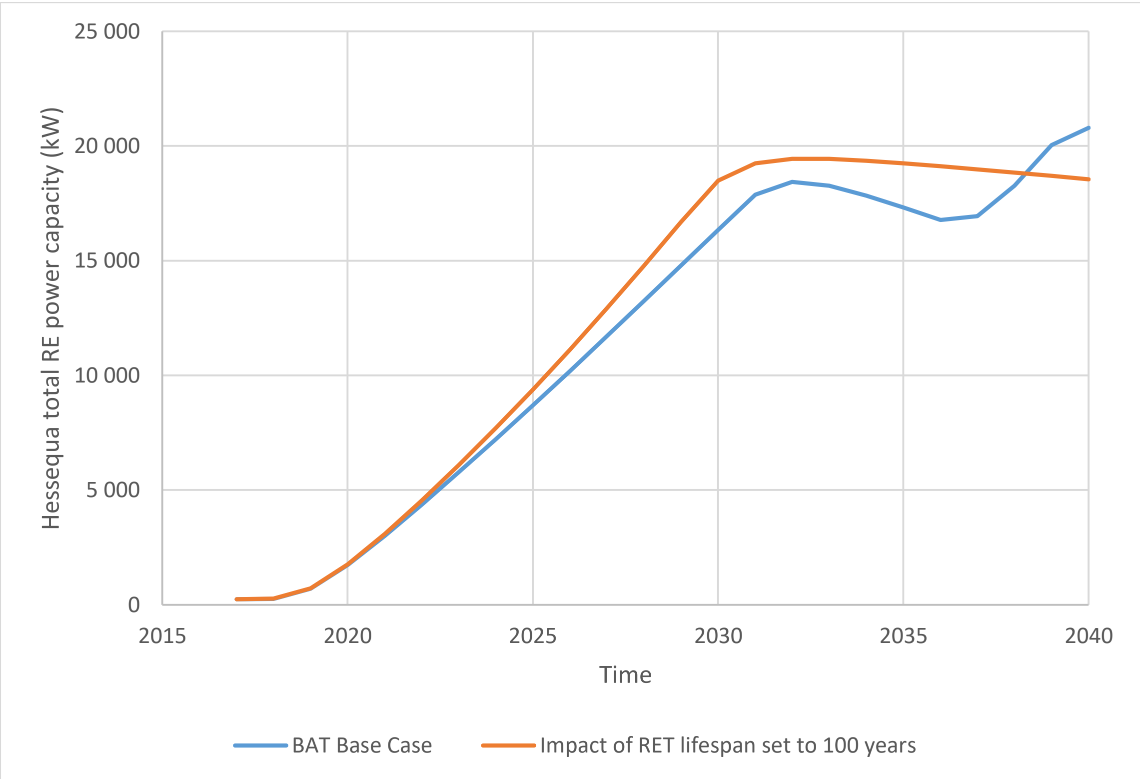

Figure 53: Behaviour Anomaly Test 2: Impact of RET lifespans set to 100 years

G 3. Sensitivity analysis test results

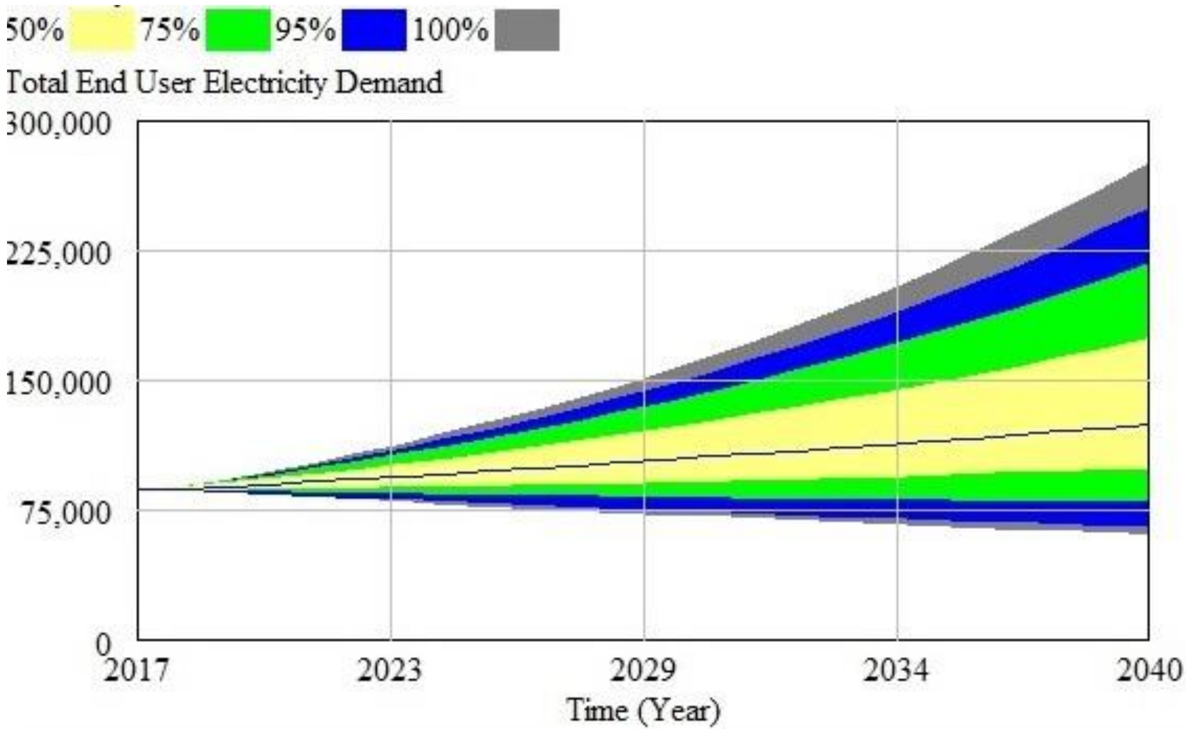

Figure 54: Sensitivity Analysis 1: Impact of varying demand elasticity of electricity price between -2 and 0 on total end user electricity demand (MWh/year)

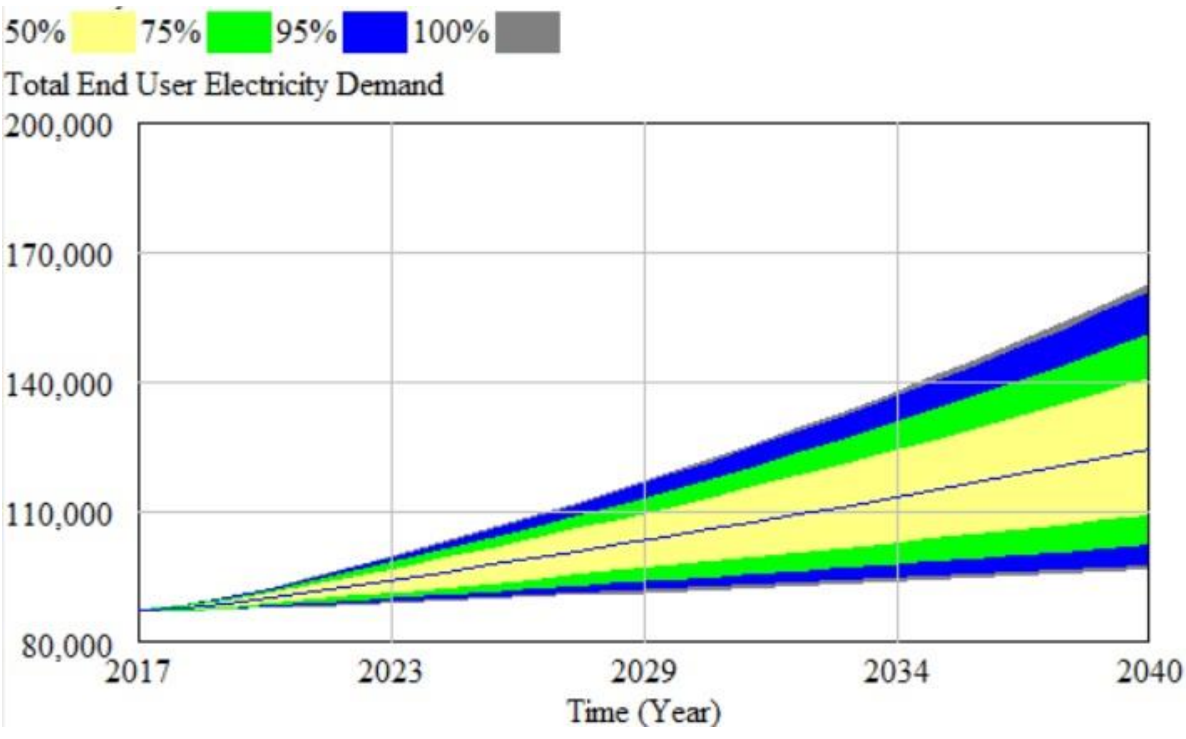

Figure 55: Sensitivity Analysis 2: Impact of varying demand elasticity of population between 0 and 1 on total end user electricity demand (MWh/year)

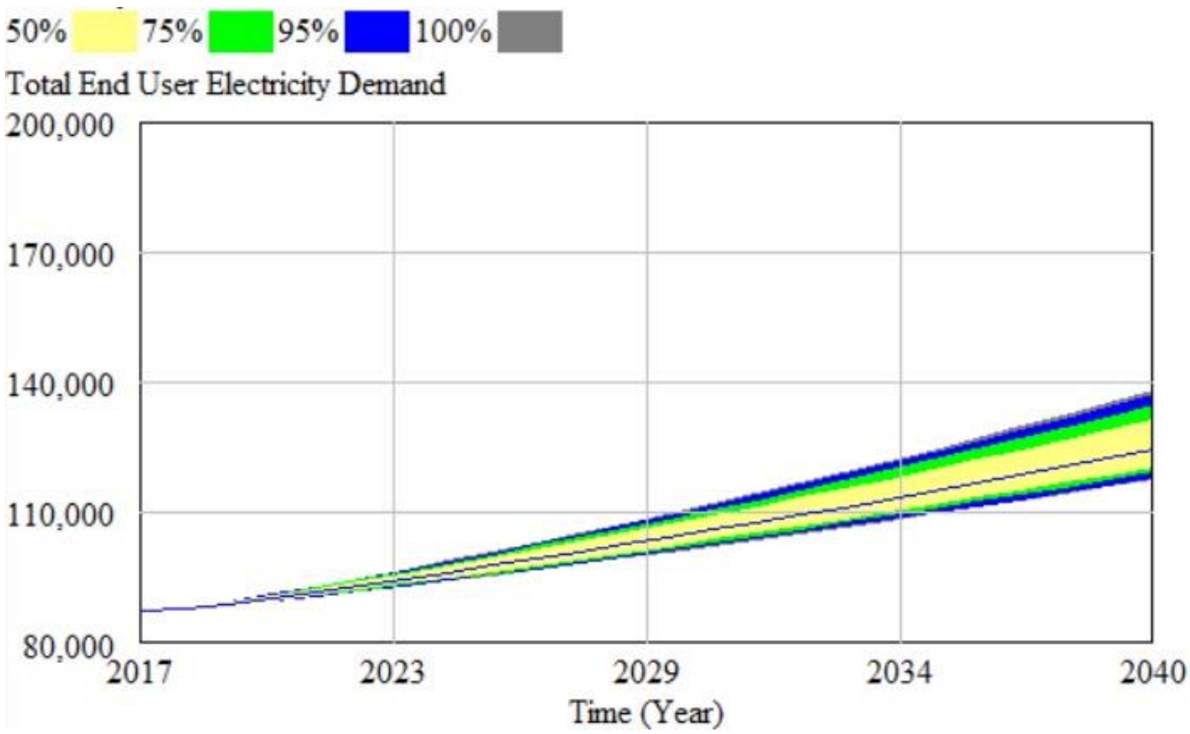

Figure 56: Sensitivity Analysis 3: Impact of varying demand elasticity of GDPR 0 and 1.5 on total end user electricity demand (MWh/year)

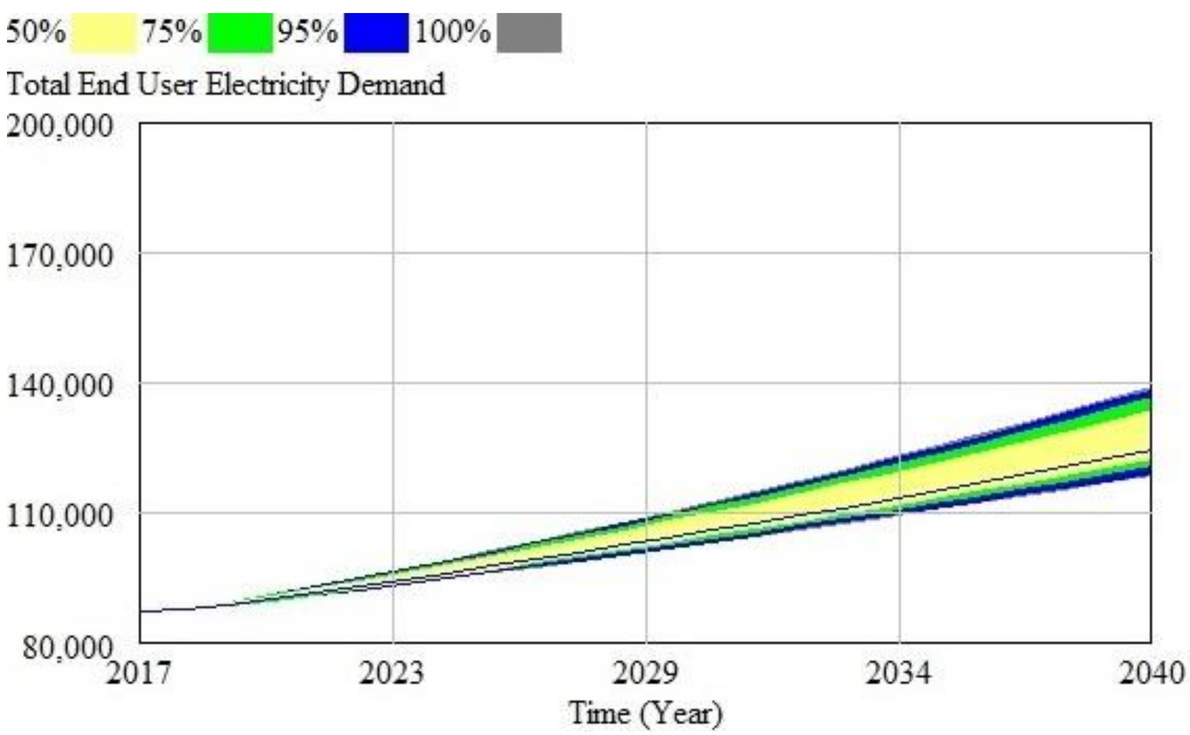

Figure 57: Sensitivity Analysis 4: Impact of varying demand elasticity of GDPR per capita 0 and 1 on total end user electricity demand (MWh/year)

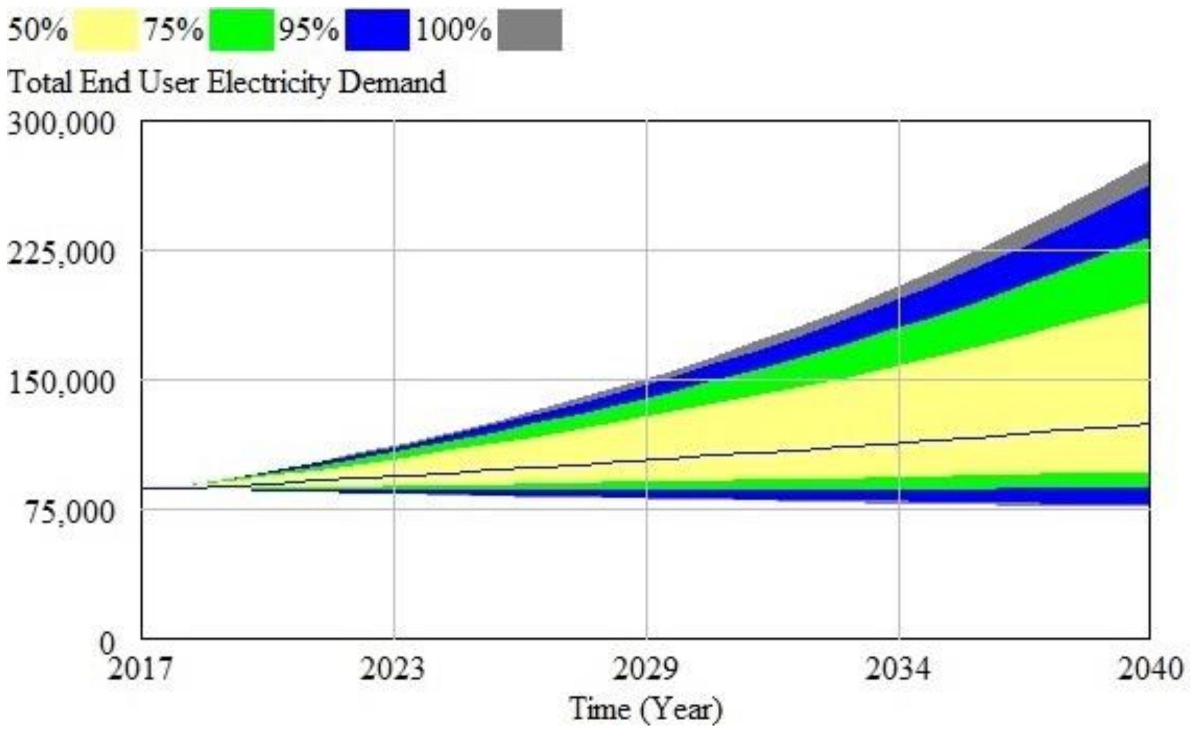

Figure 58: Sensitivity Analysis 5: Impact of varying real GDPR growth rate between -4% and 12% on total end user electricity demand (MWh/year)

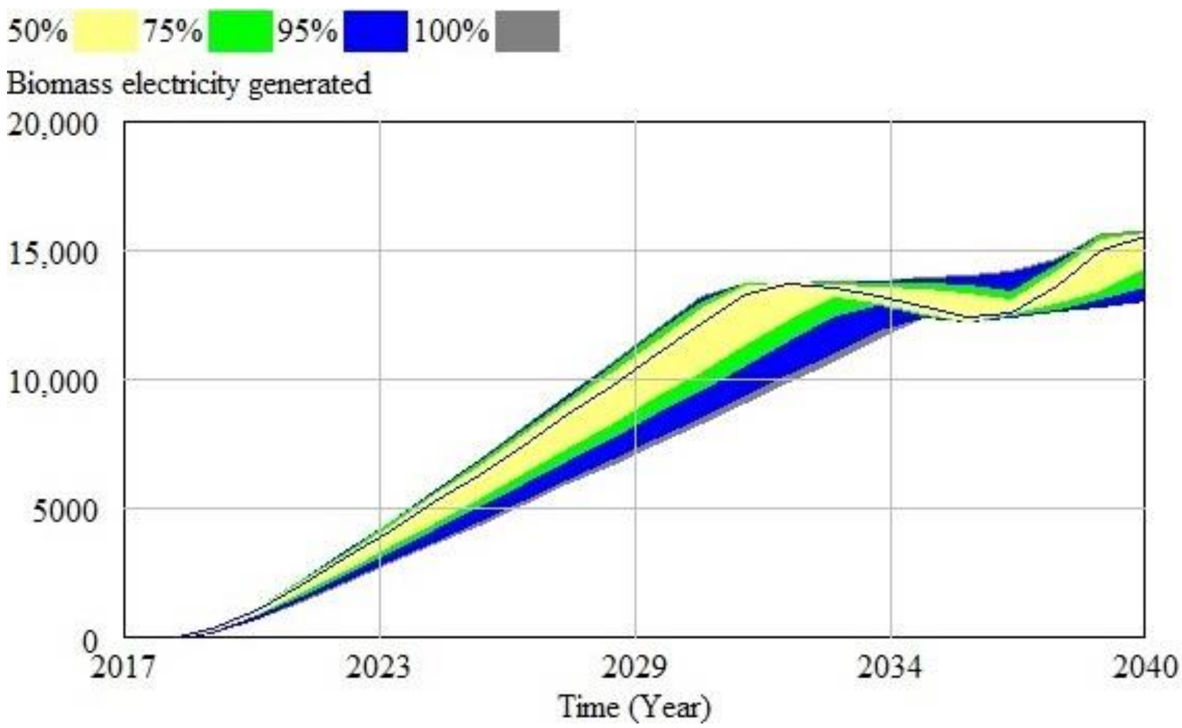

Figure 59: Sensitivity Analysis 6: Impact of varying biomass power capacity factor between 0.202 and 0.958 on biomass electricity generated (MWh/year)

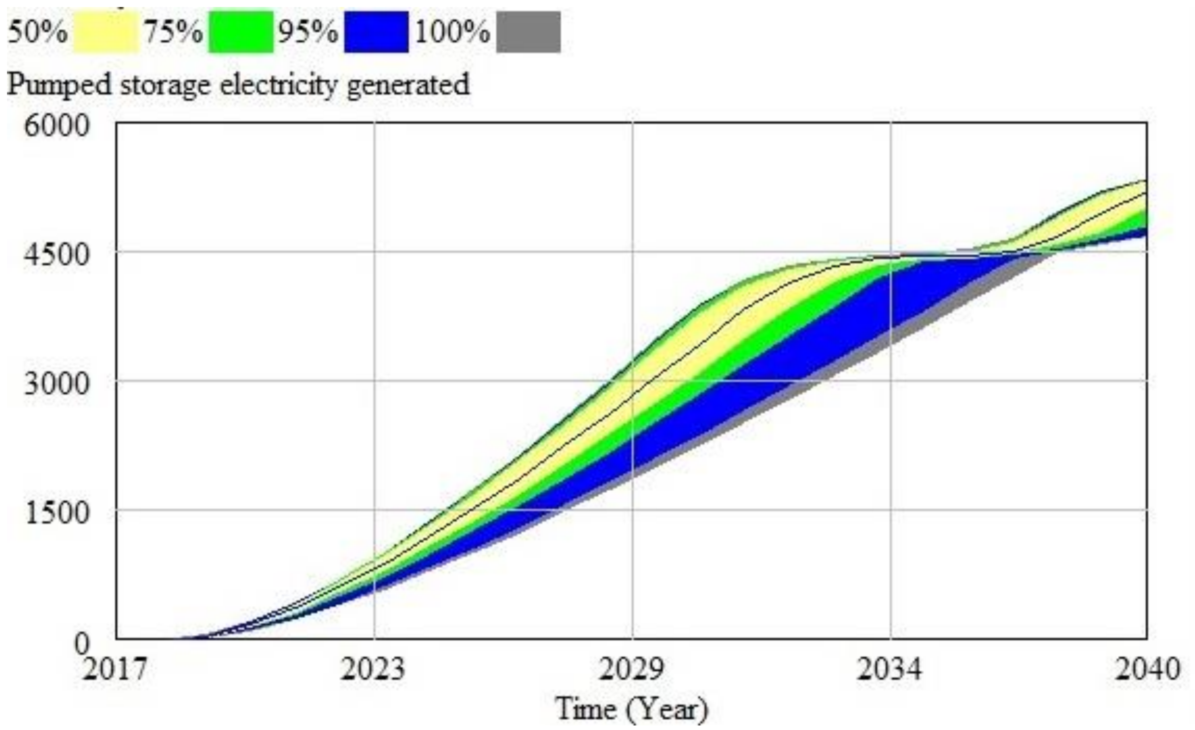

Figure 60: Sensitivity Analysis 7: Impact of varying pumped storage capacity factor between 0.115 and 0.947 on pumped storage electricity generated (MWh/year)

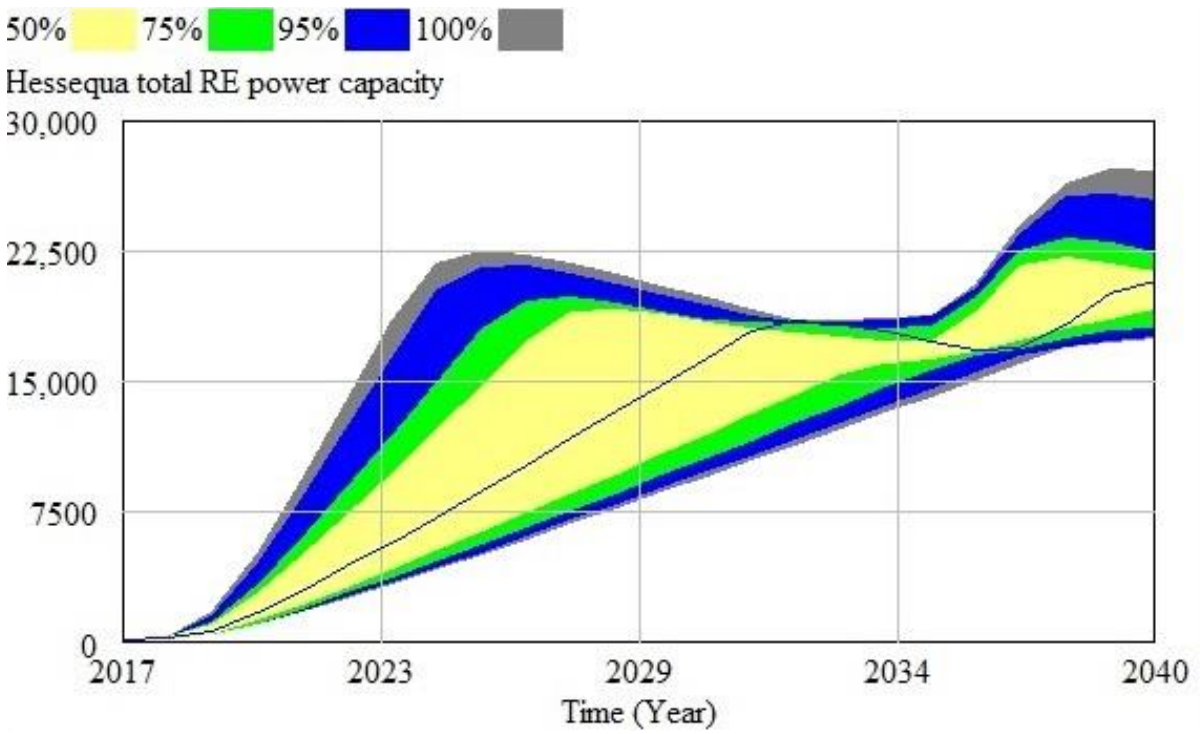

Figure 61: Sensitivity Analysis 8: Impact of varying ZAR-US$ exchange rate between 4 ZAR/US$ and 25 ZAR/US$ on Hessequa's total renewable energy power capacity (kW)

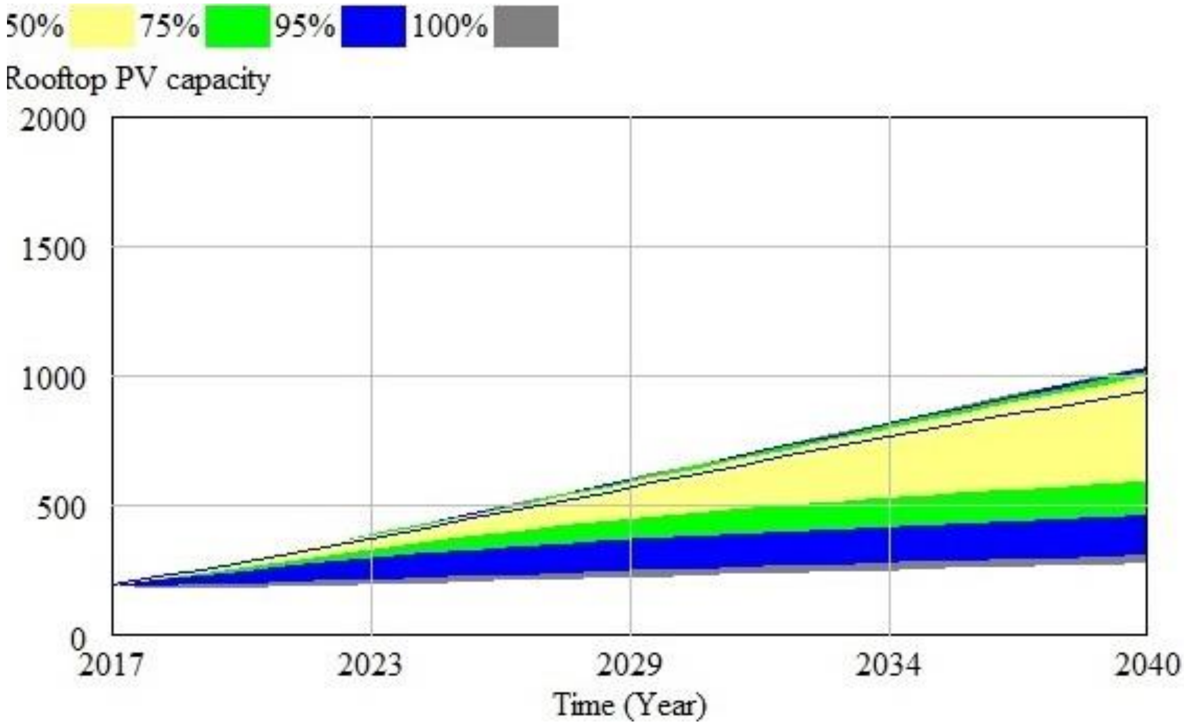

Figure 62: Sensitivity Analysis 9.1: Impact of varying the average residential rooftop PV capacity between 1 kW and 8 kW on rooftop PV capacity (kW).

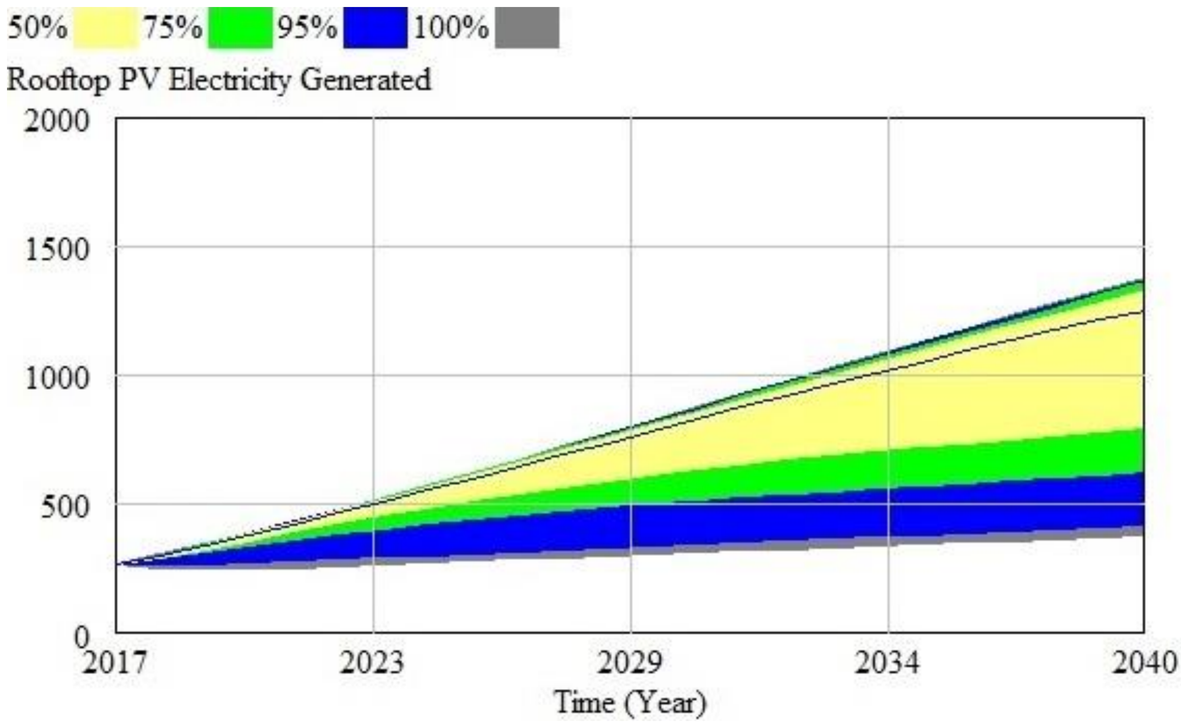

Figure 63: Sensitivity Analysis 9.2: Impact of varying the average residential rooftop PV capacity between 1 kW and 8 kW on rooftop PV electricity generated (MWh/year)

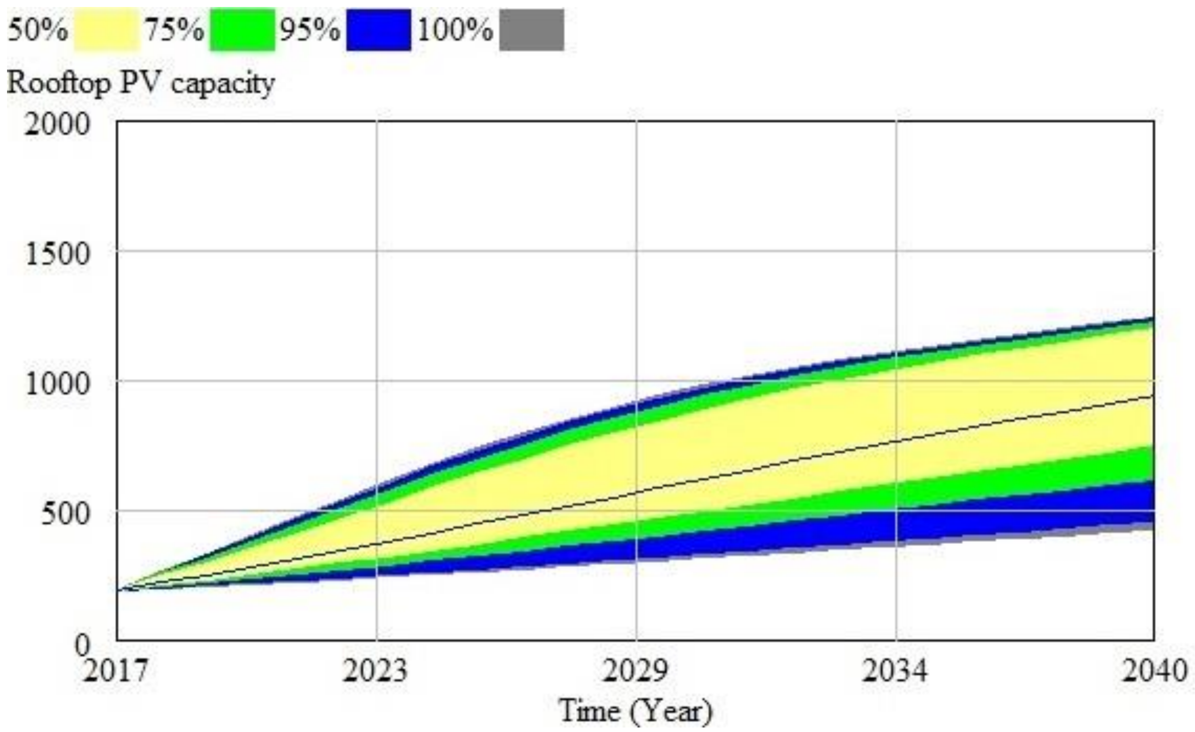

Figure 64: Sensitivity Analysis 10.1: Impact of varying the base installation rate of rooftop PV systems between 20 kW/year and 180 kW/year on rooftop PV capacity (kW)

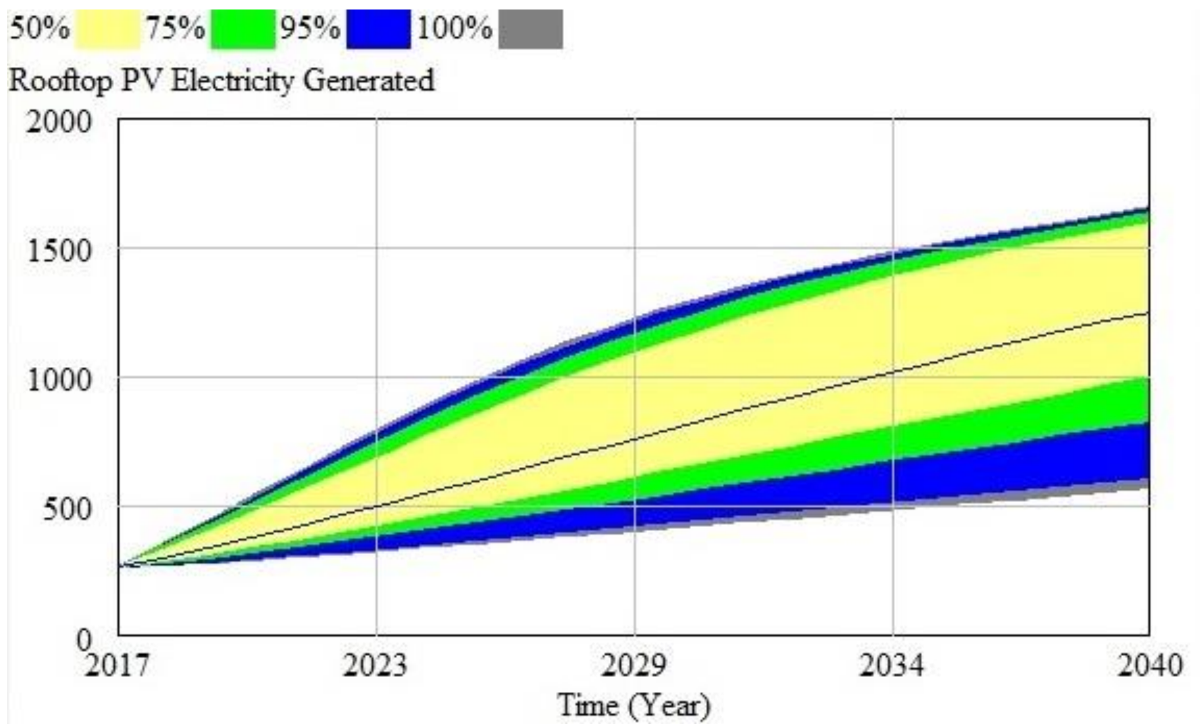

Figure 65: Sensitivity Analysis 10.2: Impact of varying the base installation rate of rooftop PV systems between 20 kW/year and 180 kW/year on rooftop PV electricity generated (kW/year)

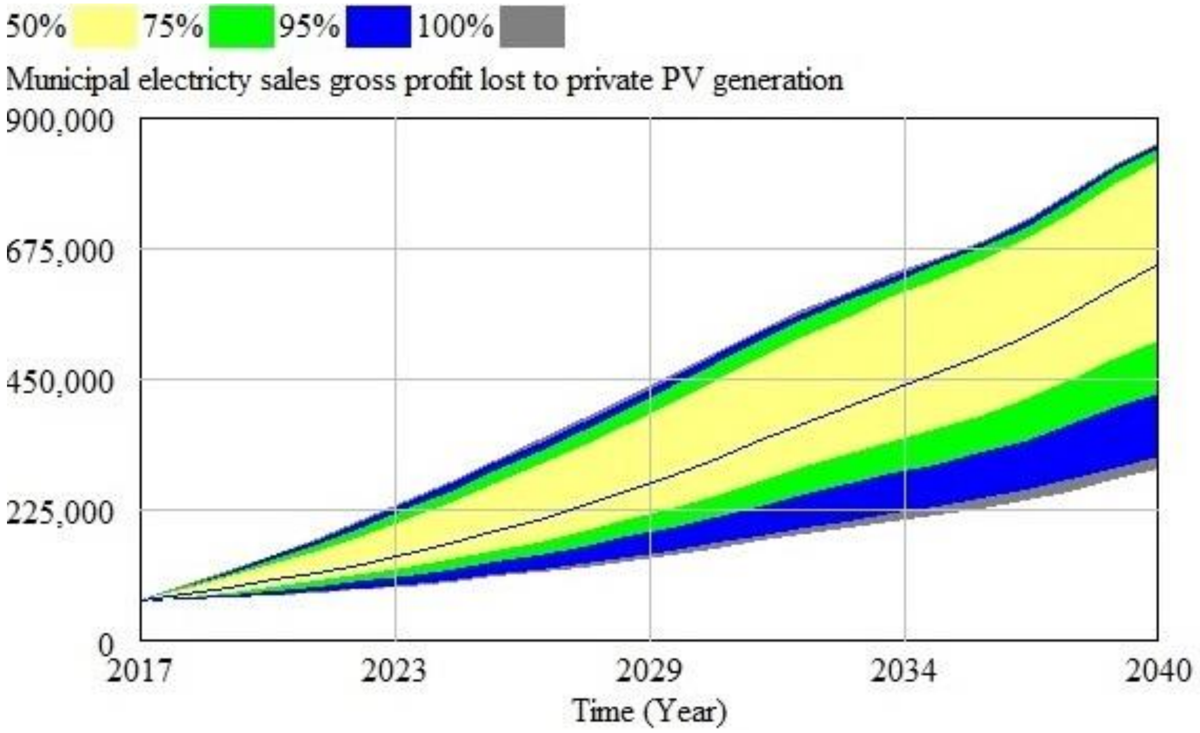

Figure 66: Sensitivity Analysis 10.3: Impact of varying the base installation rate of rooftop PV systems between 20 kW/year and 180 kW/year on municipal electricity sales gross profit lost to private PV generation (R/year)

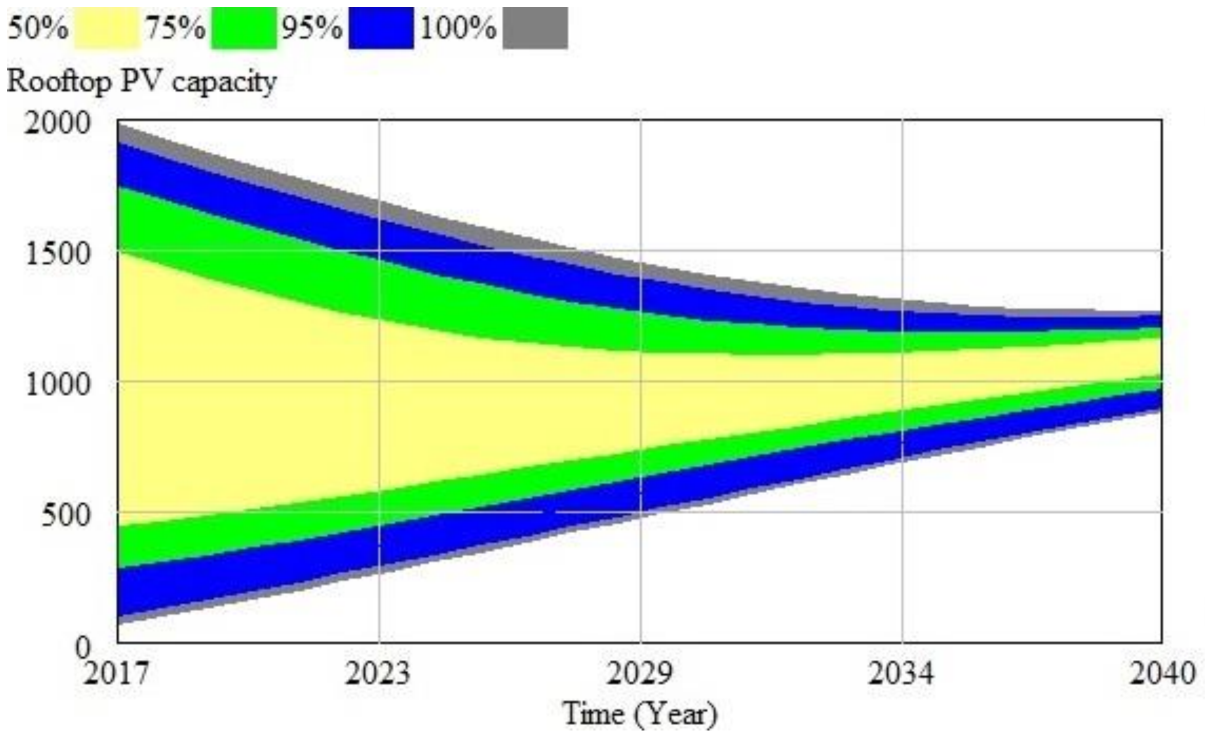

Figure 67: Sensitivity Analysis 11.1: Impact of varying the initial rooftop PV capacity between 50 kW and 2000 kW on rooftop PV capacity (kW)

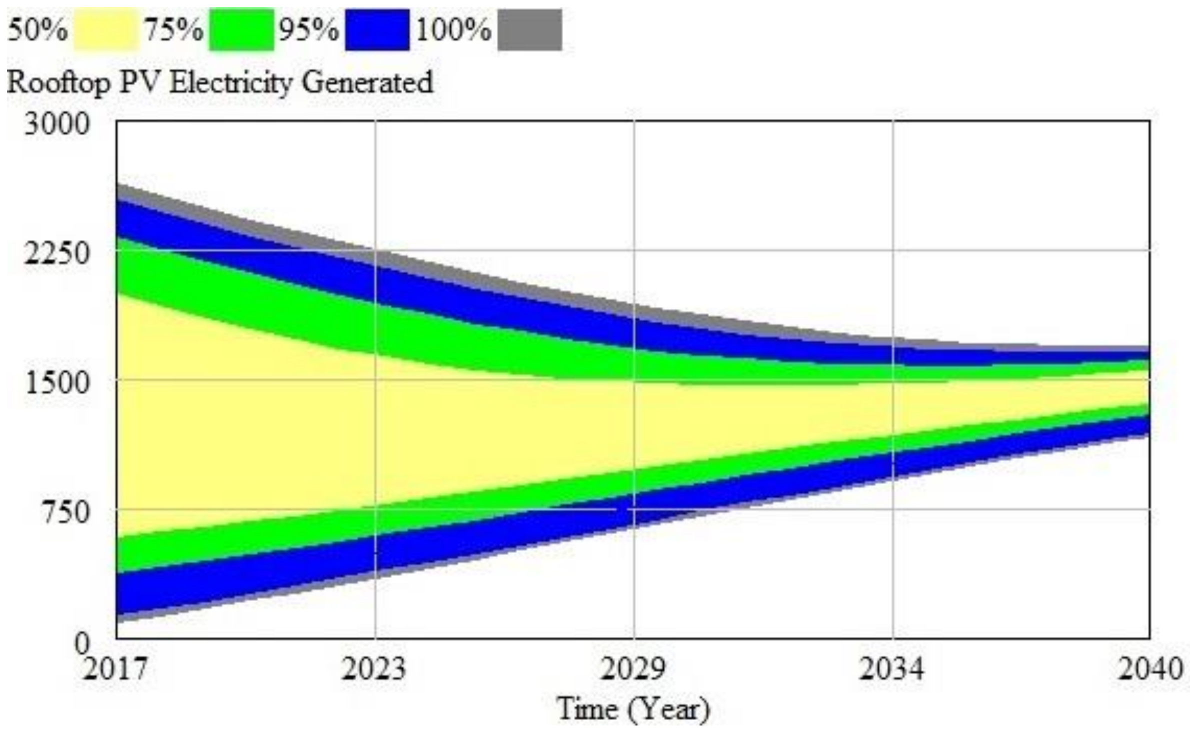

Figure 68: Sensitivity Analysis 11.2: Impact of varying the initial rooftop PV capacity between 50 kW and 2000 kW on rooftop PV electricity generated (MWh/year)

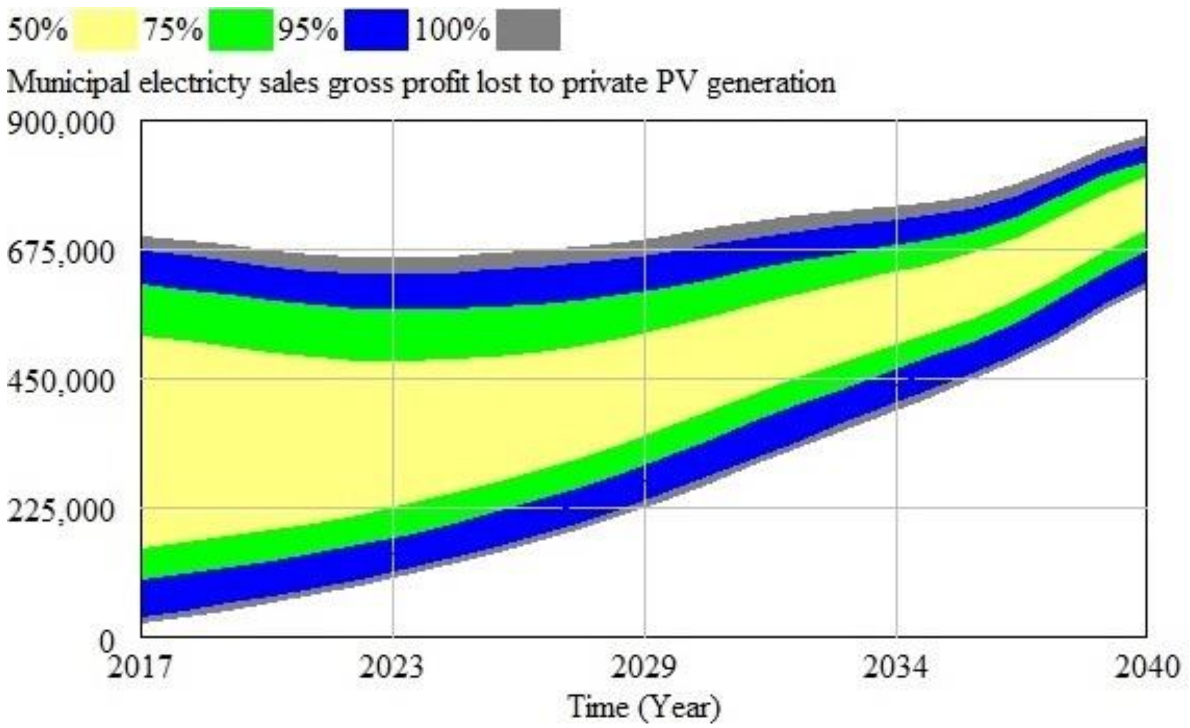

Figure 69: Sensitivity Analysis 11.3: Impact of varying the initial rooftop PV capacity between 50 kW and 2000 kW on municipal electricity sales gross profit lost to private PV generation (R/year)

Appendix H: Alternative Scenario Results

Table 46: Alternative scenario simulation results summary

Variable	Default values			
GDPR investment fraction	1.5%			
RE Generation Goal	33.3%			
Rooftop PV Compensation	Yes (50%)			
Scenario Number:	**6**	**7**	**8**	
Variable	**Single RET Options**			
REGGG Filled Fraction Solar PV	100.0%	0.0%	0.0%	
REGGG Filled Fraction Wind Power	0.0%	100.0%	0.0%	
REGGG Filled Fraction Biomass Power	0.0%	0.0%	100.0%	
REGGG Filled Fraction Pumped Storage	0.0%	0.0%	0.0%	
Scenario Number:	**9**	**10**	**11**	
Variable	**No Storage Mixes**			
REGGG Filled Fraction Solar PV	70.0%	50.0%	20.0%	
REGGG Filled Fraction Wind Power	20.0%	30.0%	10.0%	
REGGG Filled Fraction Biomass Power	10.0%	20.0%	70.0%	
REGGG Filled Fraction Pumped Storage	0.0%	0.0%	0.0%	
Scenario Number:	**12**	**13**	**14**	**15**
Variable	**Storage Mixes**			
REGGG Filled Fraction Solar PV	50%	40%	20%	45%
REGGG Filled Fraction Wind Power	0%	30%	10%	20%
REGGG Filled Fraction Biomass Power	35%	10%	40%	25%
REGGG Filled Fraction Pumped Storage	15%	20%	30%	10%

Table 47: Simulation results of scenario 6

Variable	Year	2020	2030	2040
Scenario			6	
Hessequa total RE power capacity	kW	2 391	23 412	26 308
Rooftop PV capacity	kW	287	623	940
Utility Solar PV capacity	kW	2 104	22 789	25 368
Utility Wind power capacity	kW	0	0	0
Biomass Power Capacity	kW	0	0	0
Pumped storage capacity	kW	0	0	0
Rooftop PV Electricity Generated	MWh	382	830	1 252
Utility Solar PV Electricity Generated	MWh	4 202	45 507	50 656
Utility Wind Power electricity generated	MWh	0	0	0
Pumped storage electricity generated	MWh	0	0	0
Biomass electricity generated	MWh	0	0	0
Accumulated RET Investment	R	139 072 032	517 172 736	674 867 712
Municipal electricity sales gross profit lost to private PV generation	R	107 694	404 165	777 288
Electricity sales gross profit	R	35 121 384	71 068 560	106 344 032
Real Hessequa electricity Cost	R/kWh	0.85	0.81	0.93
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82
Local RE Jobs	Jobs	1	9	10
CO2 Reductions	t	2 531	224 265	601 386
Annual CO2 emissions	t/year	86 487	65 529	77 922
Total RE water consumption	m3/year	1 405	14 207	15 915

Table 48: Simulation results of scenario 7 and 8

Variable	Year	2020	2030	2040	2020	2030	2040
Scenario			7			8	
Hessequa total RE power capacity	kW	2 280	20 182	28 159	1 249	8 711	9 843
Rooftop PV capacity	kW	287	623	940	287	623	940
Utility Solar PV capacity	kW	29	20	13	29	20	13
Utility Wind power capacity	kW	1 964	19 539	27 206	0	0	0
Biomass Power Capacity	kW	0	0	0	933	8 068	8 890
Pumped storage capacity	kW	0	0	0	0	0	0
Rooftop PV Electricity Generated	MWh	382	830	1 252	382	830	1 252
Utility Solar PV Electricity Generated	MWh	58	39	26	58	39	26
Utility Wind Power electricity generated	MWh	3 296	32 796	45 665	0	0	0
Pumped storage electricity generated	MWh	0	0	0	0	0	0
Biomass electricity generated	MWh	0	0	0	5 048	43 679	48 127
Accumulated RET Investment	R	139 072 032	694 643 584	1 104 590 336	139 072 032	509 899 104	679 313 216
Municipal electricity sales gross profit lost to private PV generation	R	107 395	341 211	687 443	97 228	197 606	479 720
Electricity sales gross profit	R	35 024 008	59 998 720	94 051 968	31 708 152	34 747 168	65 632 448
Real Hessequa electricity Cost	R/kWh	0.85	0.92	1.04	0.89	1.17	1.27
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82	1.25	1.51	1.82
Local RE Jobs	Jobs	1	8	11	4	35	38
CO2 Reductions	t	2 140	160 089	515 841	2 458	182 082	469 388
Annual CO2 emissions	t/year	87 089	74 947	80 314	86 632	74 964	88 731
Total RE water consumption	m3/year	148	391	565	5 918	50 301	55 521

Table 49: Simulation results of scenario 9 and 10

Variable	Year	2020	2030	2040	2020	2030	2040
Scenario		9			10		
Hessequa total RE power capacity	kW	2 273	22 239	24 587	2 170	20 886	23 597
Rooftop PV capacity	kW	287	623	940	287	623	940
Utility Solar PV capacity	kW	1 432	15 506	16 936	1 022	10 865	12 108
Utility Wind power capacity	kW	480	5 267	5 754	713	7 746	8 636
Biomass Power Capacity	kW	74	843	957	147	1 652	1 913
Pumped storage capacity	kW	0	0	0	0	0	0
Rooftop PV Electricity Generated	MWh	382	830	1 252	382	830	1 252
Utility Solar PV Electricity Generated	MWh	2 859	30 963	33 819	2 042	21 696	24 178
Utility Wind Power electricity generated	MWh	805	8 840	9 658	1 198	13 002	14 496
Pumped storage electricity generated	MWh	0	0	0	0	0	0
Biomass electricity generated	MWh	402	4 563	5 183	797	8 942	10 356
Accumulated RET Investment	R	139 072 032	564 995 712	736 226 624	139 072 032	594 899 520	780 858 496
Municipal electricity sales gross profit lost to private PV generation	R	106 786	372 377	722 813	105 931	346 568	687 378
Electricity sales gross profit	R	34 825 504	65 478 888	98 891 016	34 546 536	60 940 768	94 043 048
Real Hessequa electricity Cost	R/kWh	0.85	0.87	0.99	0.86	0.91	1.04
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82	1.25	1.51	1.82
Local RE Jobs	Jobs	1	12	13	1	15	17
CO2 Reductions	t	2 430	204 670	568 124	2 378	193 624	547 877
Annual CO2 emissions	t/year	86 646	66 984	80 151	86 729	68 234	80 603
Total RE water consumption	m3/year	1 457	15 008	16 726	1 660	17 199	19 715

Table 50: Simulation results of scenario 11 and 12

Variable	Year	2020	2030	2040	2020	2030	2040
Scenario			11			12	
Hessequa total RE power capacity	kW	1 646	13 235	14 714	1 531	14 652	18 612
Rooftop PV capacity	kW	287	623	940	287	623	940
Utility Solar PV capacity	kW	488	4 314	4 624	938	9 952	12 180
Utility Wind power capacity	kW	275	2 556	2 744	0	0	0
Biomass Power Capacity	kW	595	5 741	6 406	236	2 646	3 355
Pumped storage capacity	kW	0	0	0	71	1 431	2 137
Rooftop PV Electricity Generated	MWh	382	830	1 252	382	830	1 252
Utility Solar PV Electricity Generated	MWh	975	8 615	9 234	1 873	19 874	24 322
Utility Wind Power electricity generated	MWh	461	4 291	4 606	0	0	0
Pumped storage electricity generated	MWh	0	0	0	256	5 176	7 732
Biomass electricity generated	MWh	3 224	31 079	34 679	1 276	14 325	18 163
Accumulated RET Investment	R	139 072 032	539 127 232	714 082 240	139 072 032	679 040 000	877 576 256
Municipal electricity sales gross profit lost to private PV generation	R	100 965	252 837	554 752	104 283	305 537	636 414
Electricity sales gross profit	R	32 927 008	44 458 984	75 897 936	34 009 024	53 725 792	87 070 376
Real Hessequa electricity Cost	R/kWh	0.87	1.07	1.19	0.86	0.98	1.09
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82	1.25	1.51	1.82
Local RE Jobs	Jobs	3	27	30	1	16	20
CO2 Reductions	t	2 430	187 952	499 585	1 907	161 249	495 403
Annual CO2 emissions	t/year	86 664	72 290	85 813	87 394	73 154	81 392
Total RE water consumption	m3/year	4 111	38 514	42 958	6 499	110 743	160 086

Table 51: Simulation results of scenario 13 and 14

Variable	Year	2020	2030	2040	2020	2030	2040
Scenario		13			14		
Hessequa total RE power capacity	kW	1 636	15 363	20 659	1 147	10 191	14 135
Rooftop PV capacity	kW	287	623	940	287	623	940
Utility Solar PV capacity	kW	652	6 624	8 579	334	3 116	3 928
Utility Wind power capacity	kW	559	5 896	7 645	182	1 843	2 329
Biomass Power Capacity	kW	58	629	847	226	2 359	3 110
Pumped storage capacity	kW	81	1 592	2 649	119	2 250	3 828
Rooftop PV Electricity Generated	MWh	382	830	1 252	382	830	1 252
Utility Solar PV Electricity Generated	MWh	1 302	13 227	17 130	667	6 223	7 843
Utility Wind Power electricity generated	MWh	939	9 896	12 832	306	3 094	3 910
Pumped storage electricity generated	MWh	292	5 758	9 584	429	8 139	13 851
Biomass electricity generated	MWh	312	3 403	4 585	1 222	12 769	16 835
Accumulated RET Investment	R	139 072 032	694 643 584	1 064 881 088	139 072 032	694 643 520	1 037 353 280
Municipal electricity sales gross profit lost to private PV generation	R	106 090	326 279	659 199	103 850	275 443	572 654
Electricity sales gross profit	R	34 598 440	57 373 008	90 187 696	33 867 736	48 434 032	78 347 184
Real Hessequa electricity Cost	R/kWh	0.86	0.95	1.07	0.86	1.04	1.17
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82	1.25	1.51	1.82
Local RE Jobs	Jobs	1	8	11	1	13	17
CO_2 Reductions	t	1 723	143 466	486 503	1 459	123 638	437 962
Annual CO_2 emissions	t/year	87 661	76 743	83 429	88 036	80 370	87 283
Total RE water consumption	m3/year	5 842	106 137	173 859	9 013	155 169	257 550

Table 52: Simulation results of scenario 15

Variable	Year	2020	2030	2040
Scenario		15		
Hessequa total RE power capacity	kW	1 781	17 002	21 605
Rooftop PV capacity	kW	287	623	940
Utility Solar PV capacity	kW	845	8 876	11 005
Utility Wind power capacity	kW	434	4 685	5 814
Biomass Power Capacity	kW	168	1 872	2 405
Pumped storage capacity	kW	47	946	1 441
Rooftop PV Electricity Generated	MWh	382	830	1 252
Utility Solar PV Electricity Generated	MWh	1 687	17 723	21 976
Utility Wind Power electricity generated	MWh	729	7 864	9 758
Pumped storage electricity generated	MWh	170	3 422	5 213
Biomass electricity generated	MWh	909	10 137	13 022
Accumulated RET Investment	R	139 072 032	679 040 064	880 192 832
Municipal electricity sales gross profit lost to private PV generation	R	105 234	322 807	662 021
Electricity sales gross profit	R	34 319 184	56 762 600	90 573 864
Real Hessequa electricity Cost	R/kWh	0.86	0.95	1.06
Real Hessequa Electricity Tariff	R/kWh	1.25	1.51	1.82
Local RE Jobs	Jobs	1	14	17
CO2 Reductions	t	2 029	167 276	510 903
Annual CO2 emissions	t/year	87 225	72 334	80 360
Total RE water consumption	m3/year	4 568	75 502	110 700

Appendix I: HessREM Stock-and-Flow Diagrams

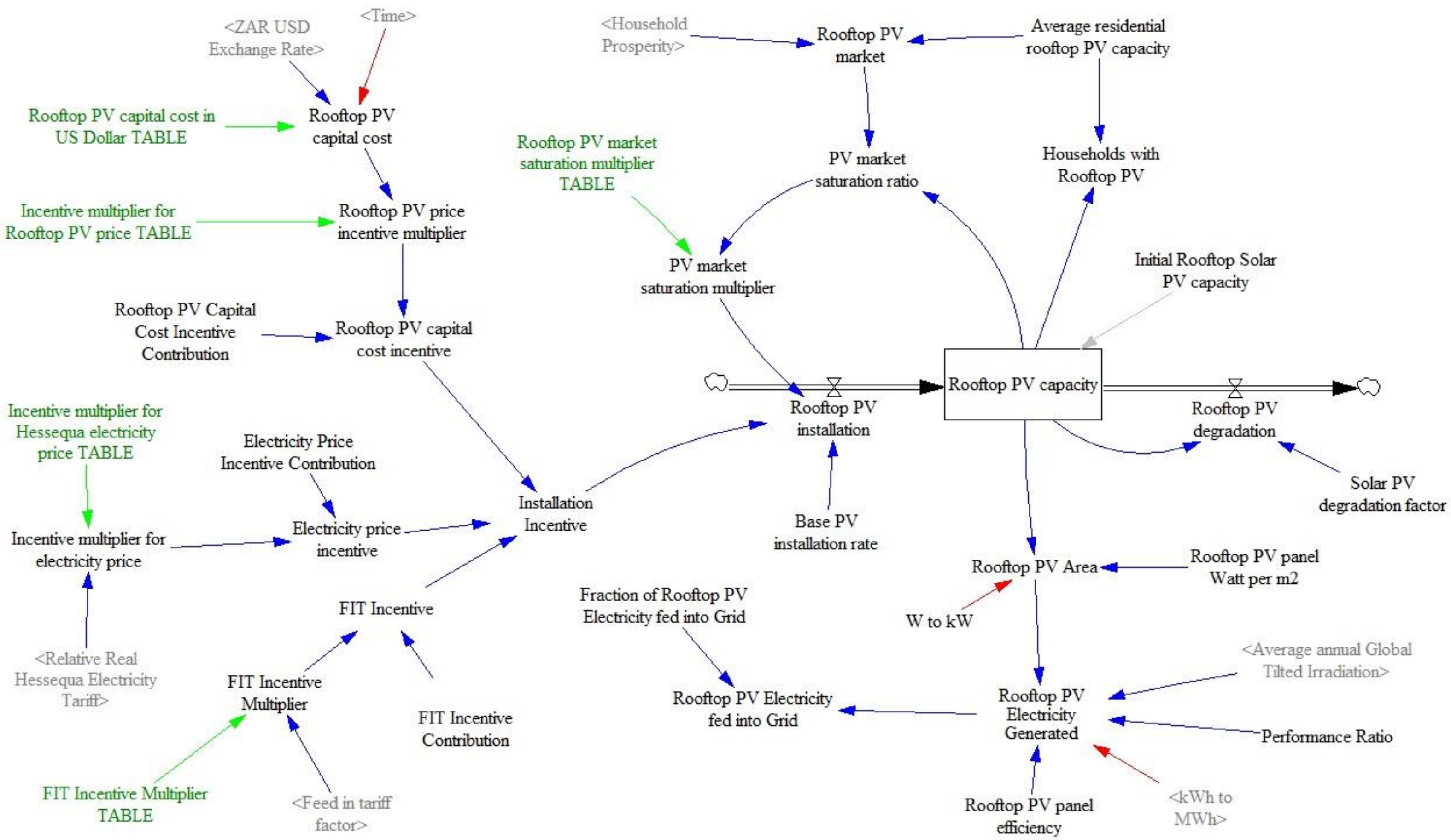

Figure 70: Rooftop PV sub-model

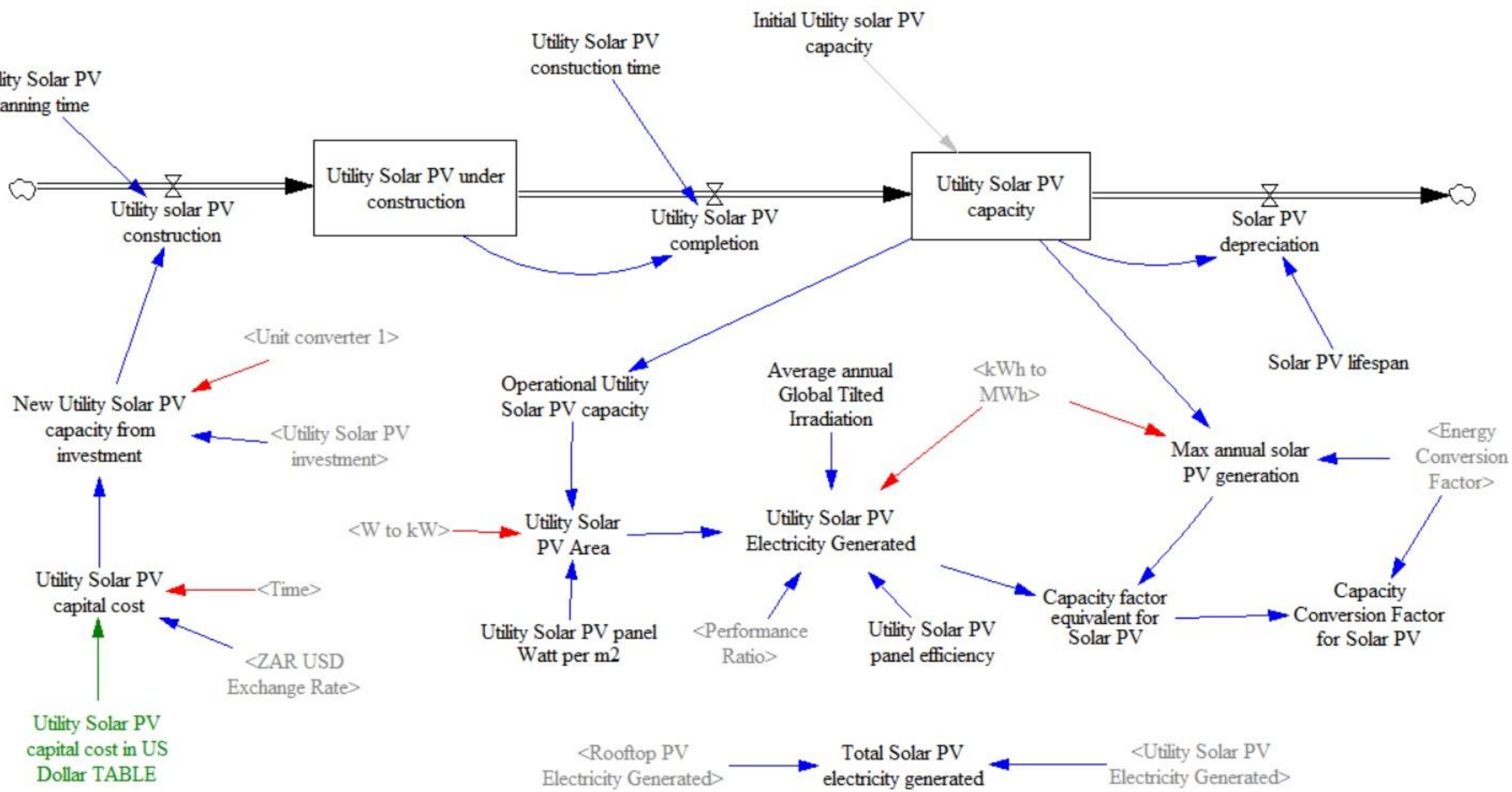

Figure 71: Utility solar PV sub-model

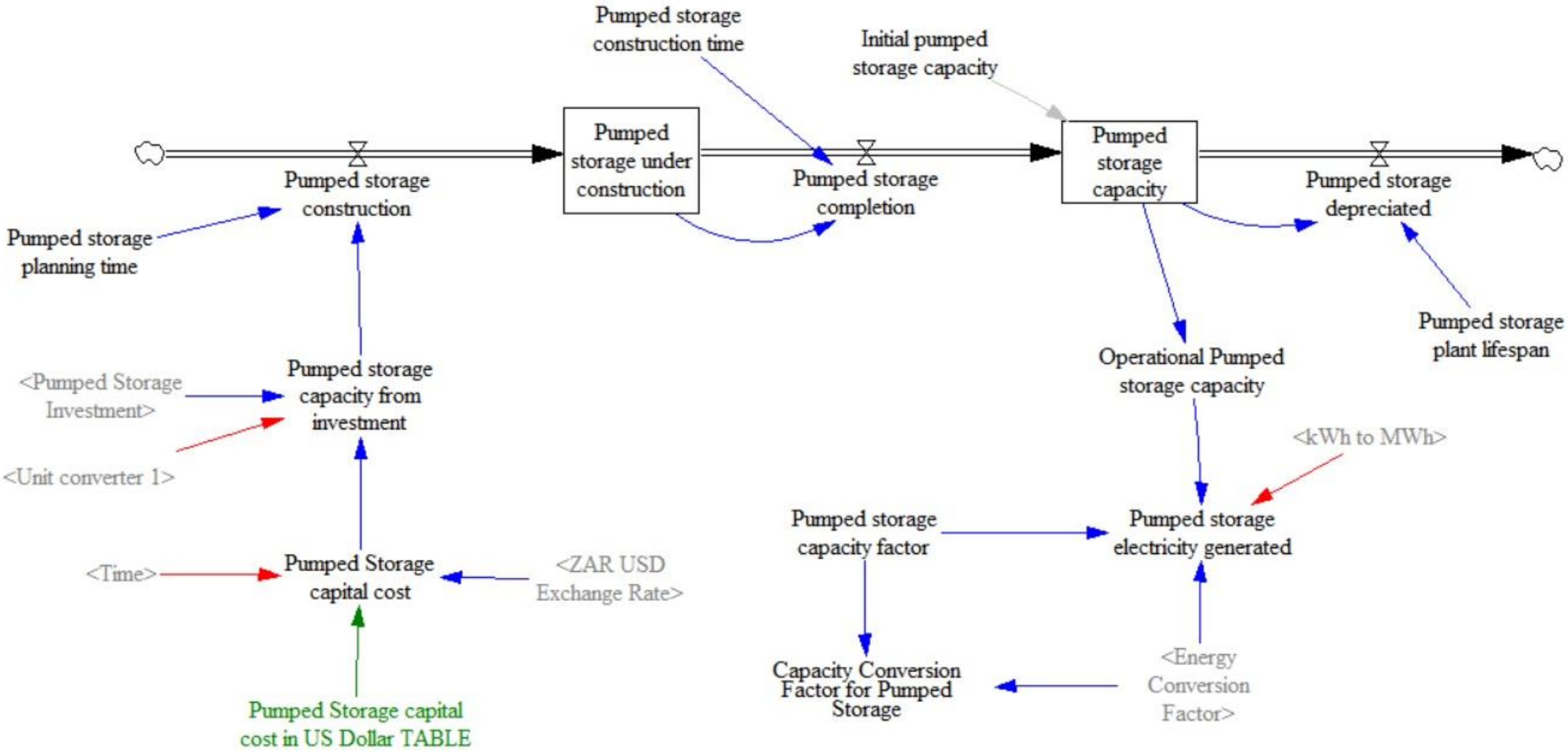

Figure 72: Pumped storage sub-model

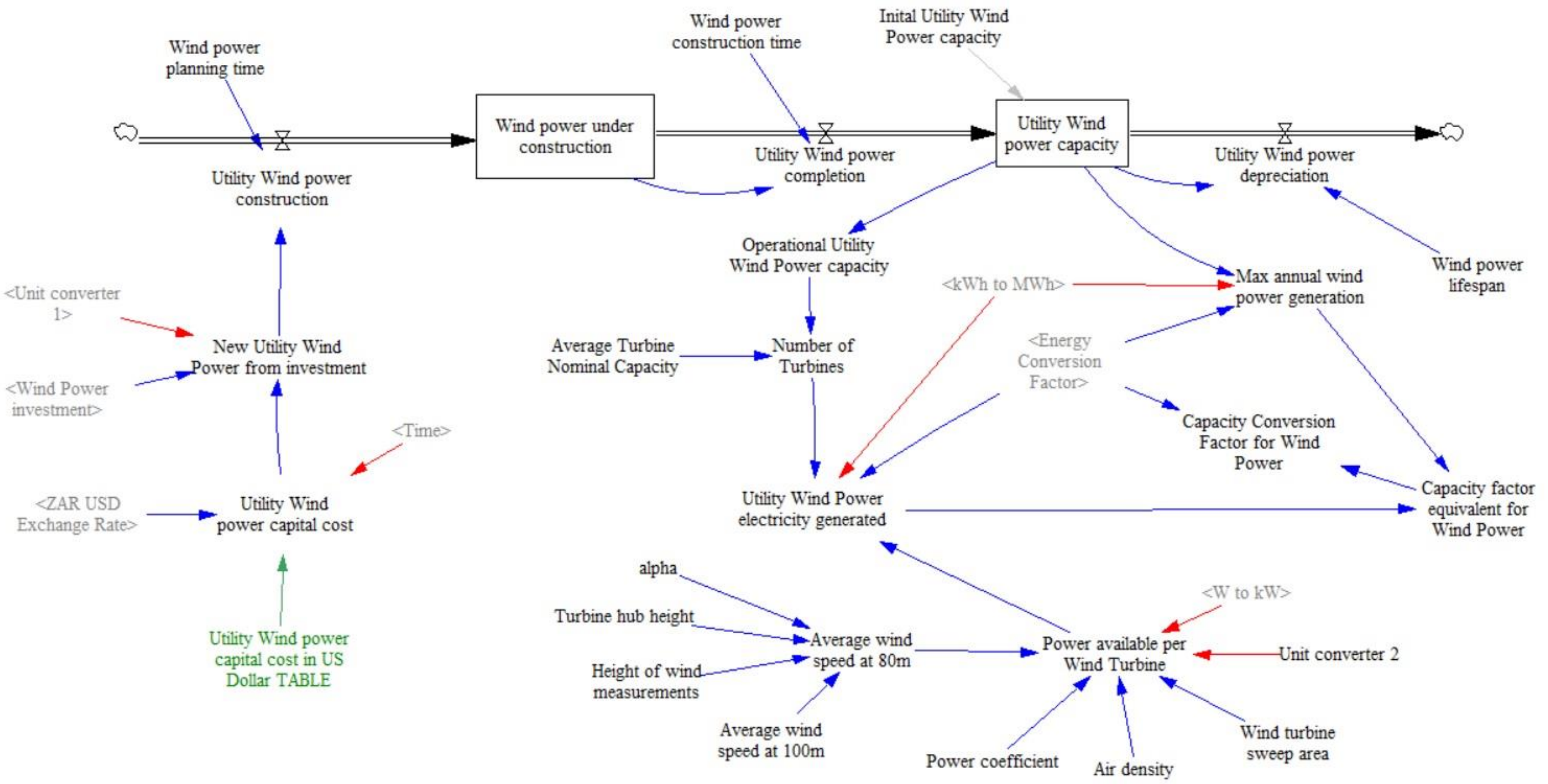

Figure 73: Utility wind power sub-model

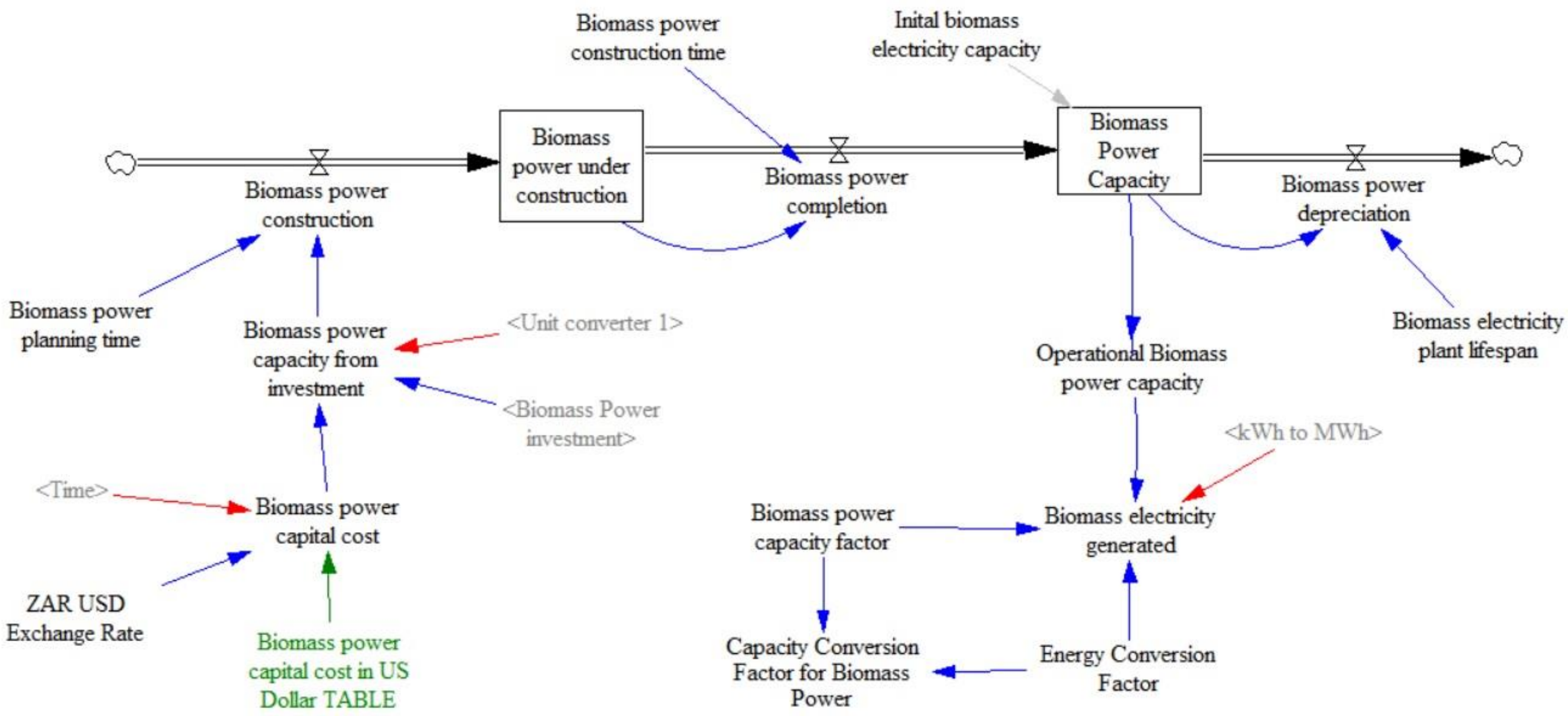

Figure 74: Biomass power sub-model

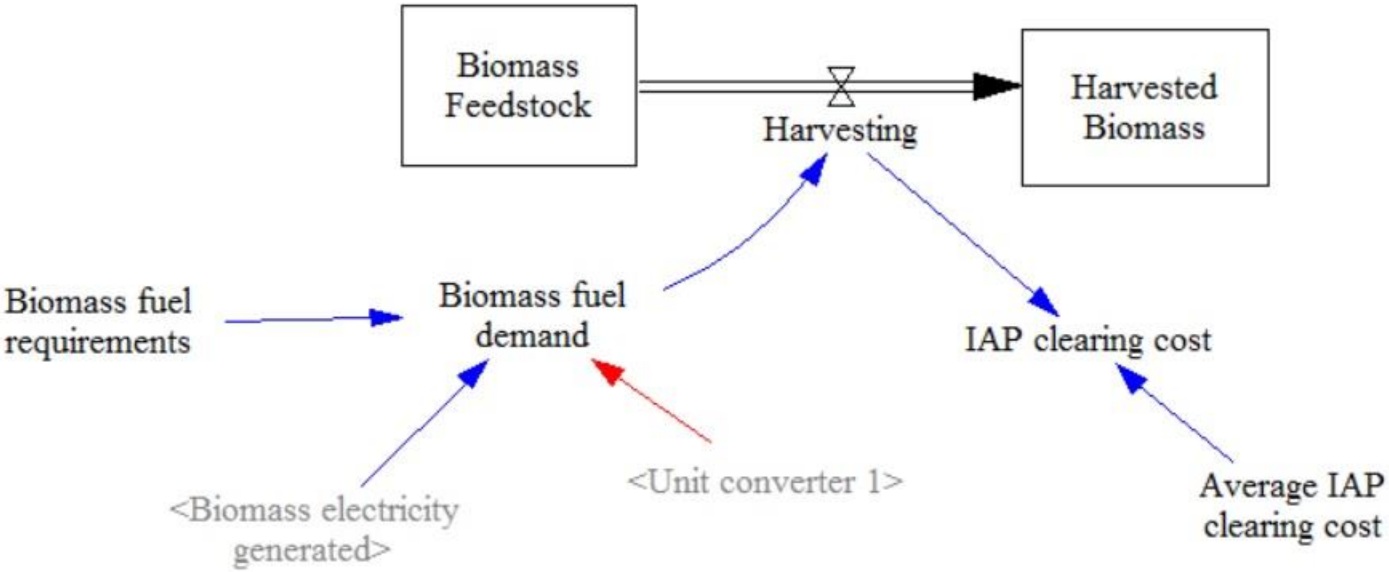

Figure 75: Biomass fuel sub-model

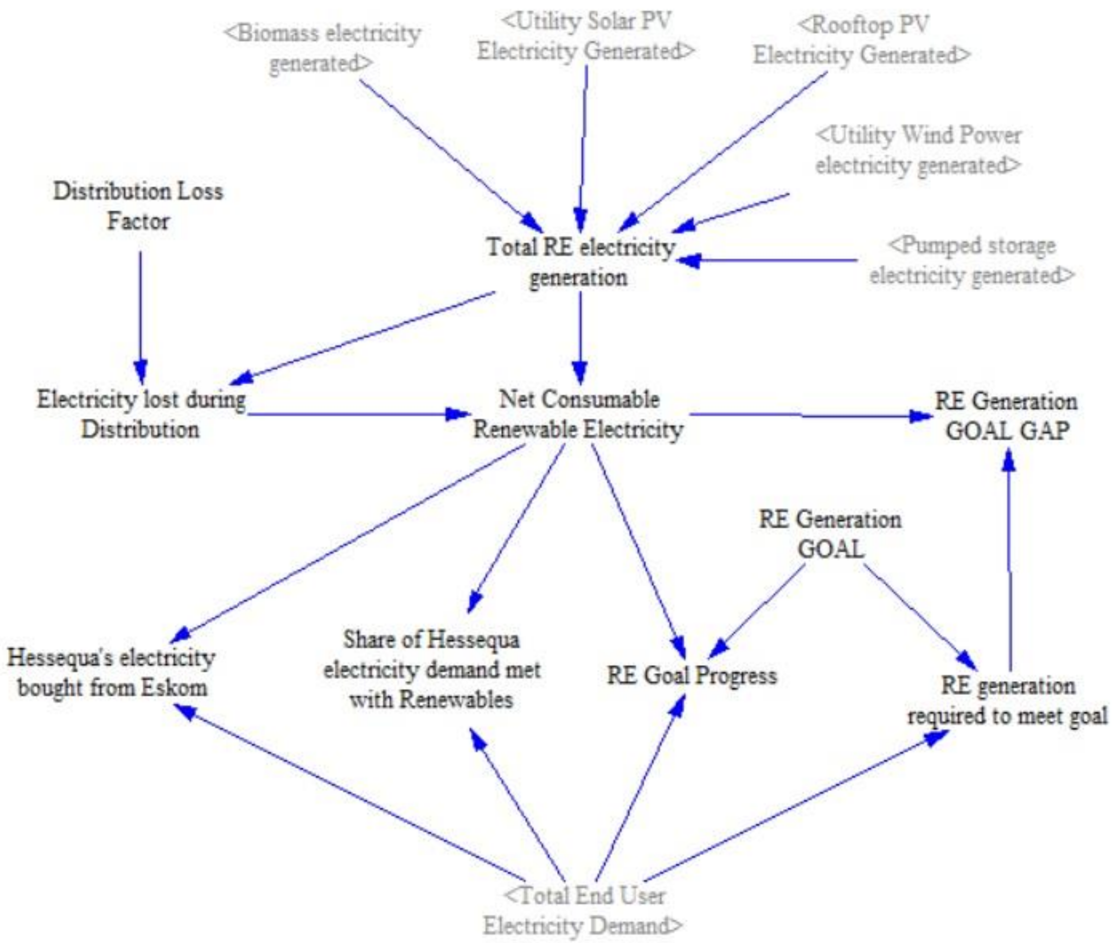

Figure 76: Electricity supply sub-model 1

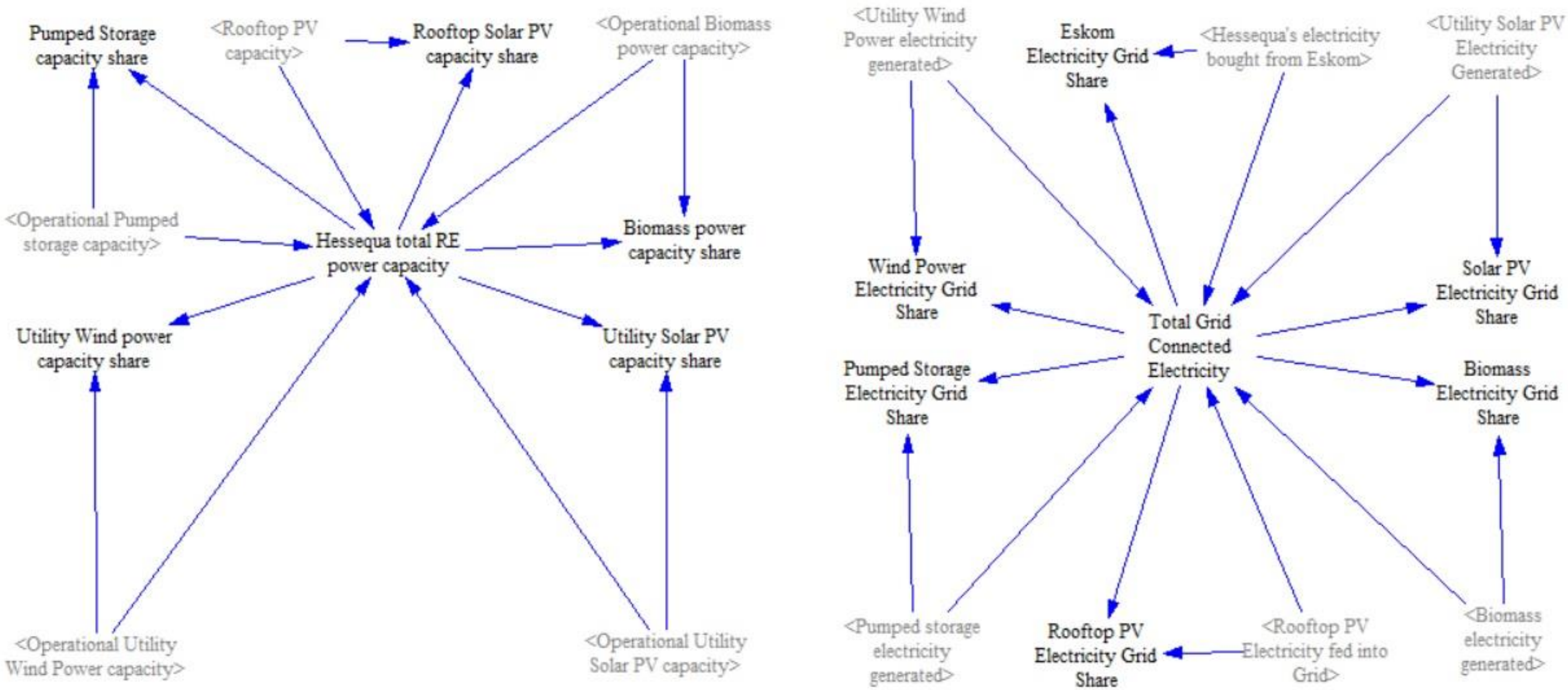

Figure 77: Electricity supply sub-model 2

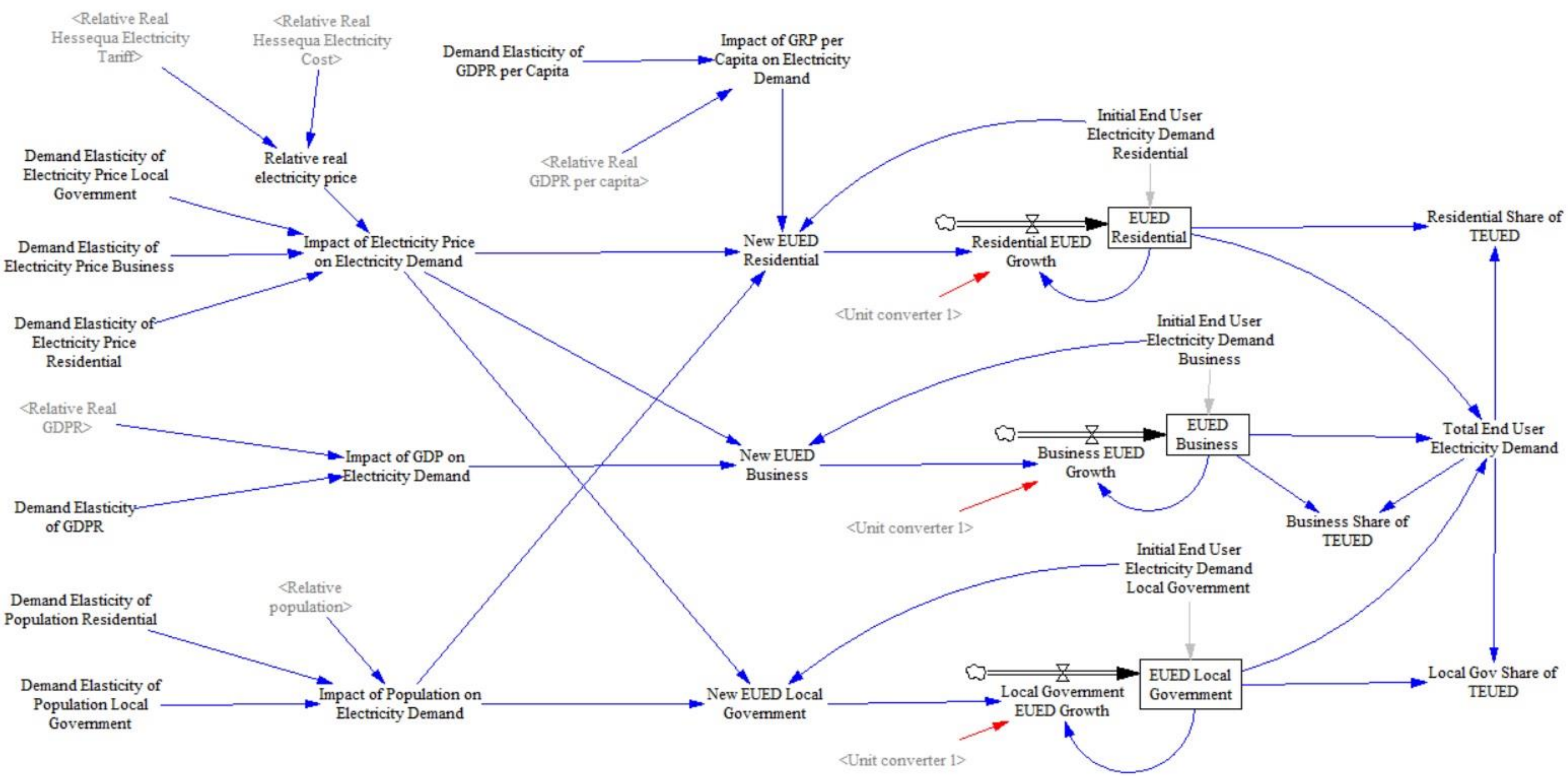

Figure 78: Electricity demand sub-model

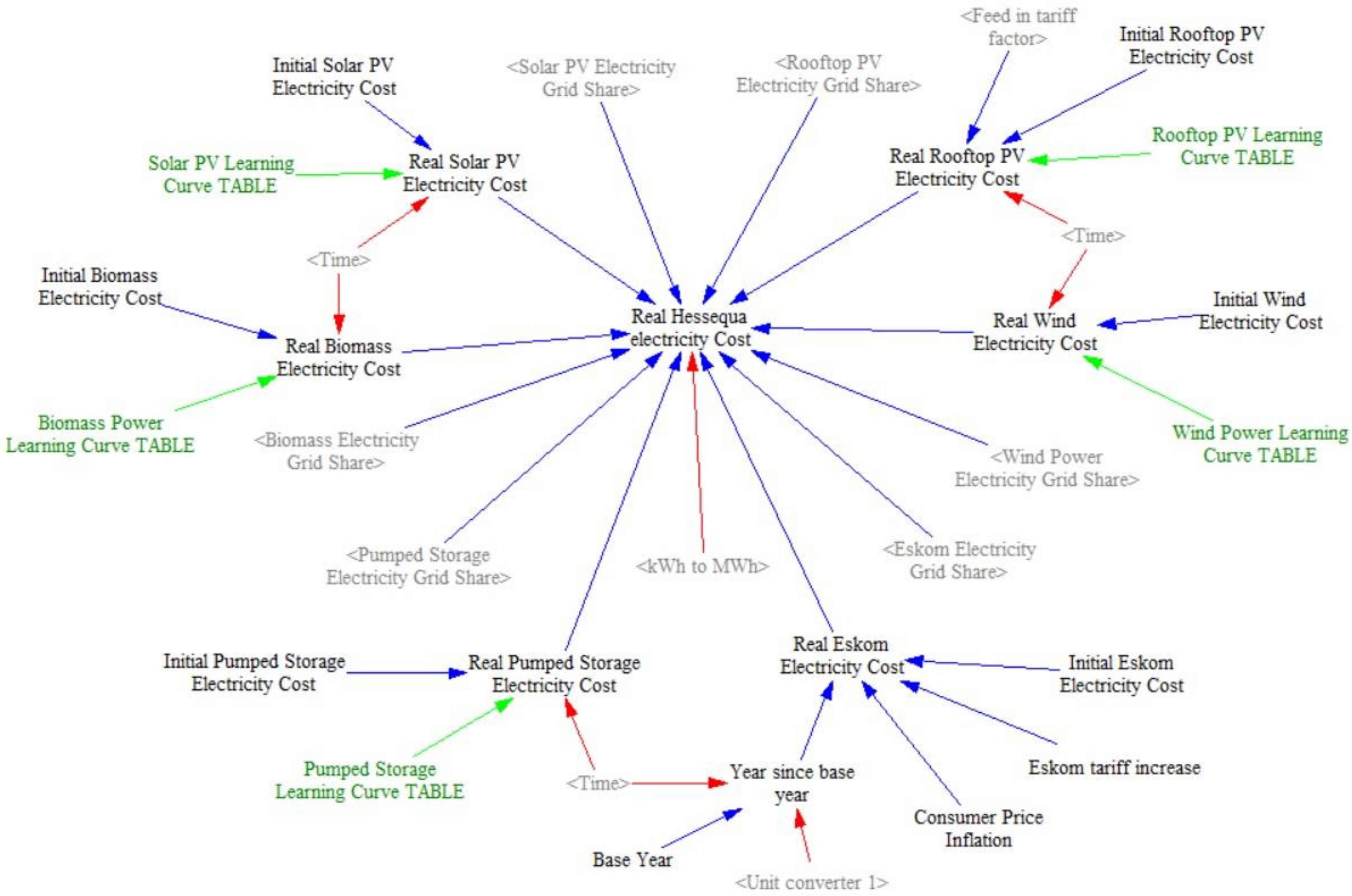

Figure 79: Real electricity cost sub-model

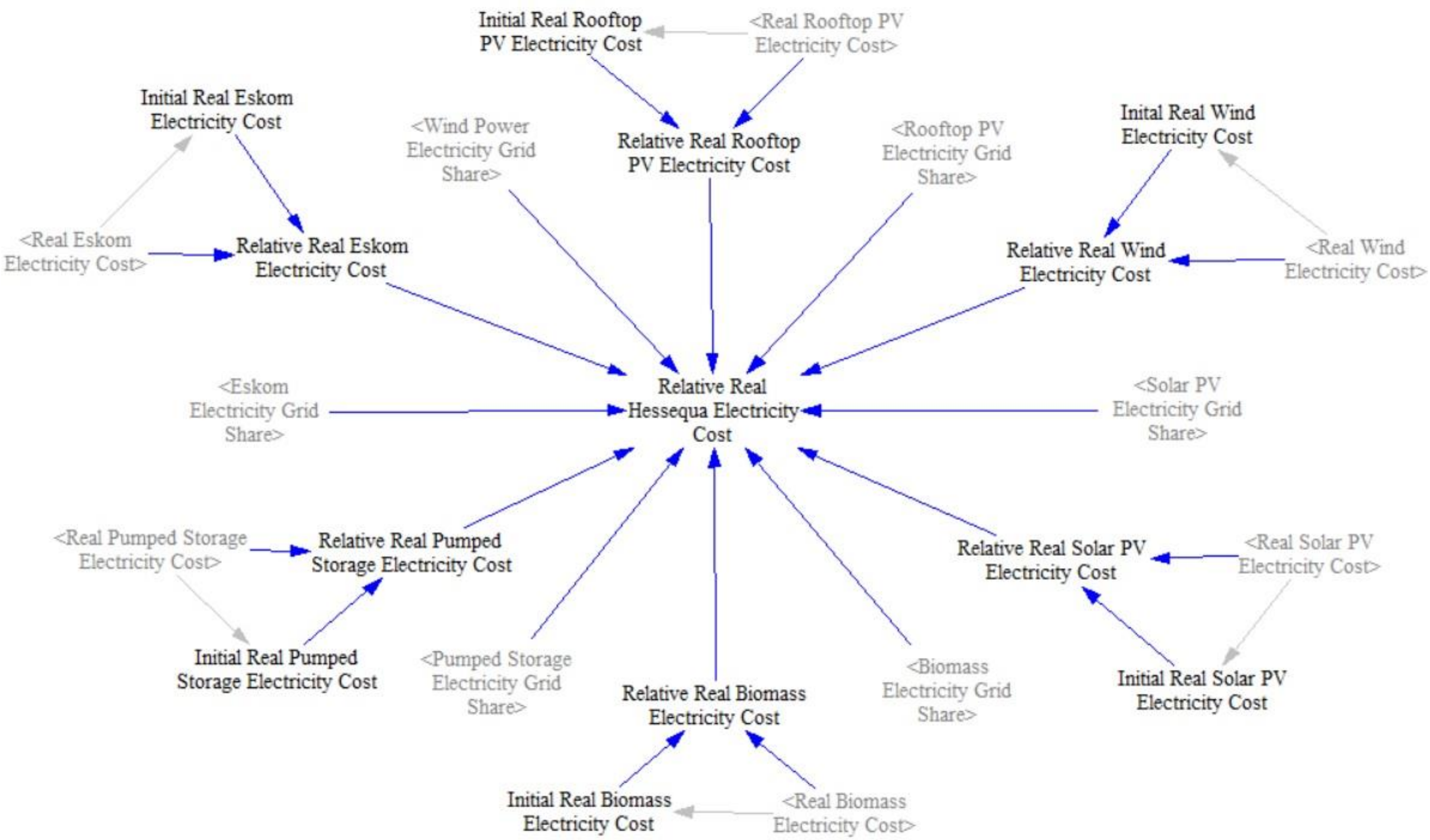

Figure 80: Relative real electricity cost sub-model

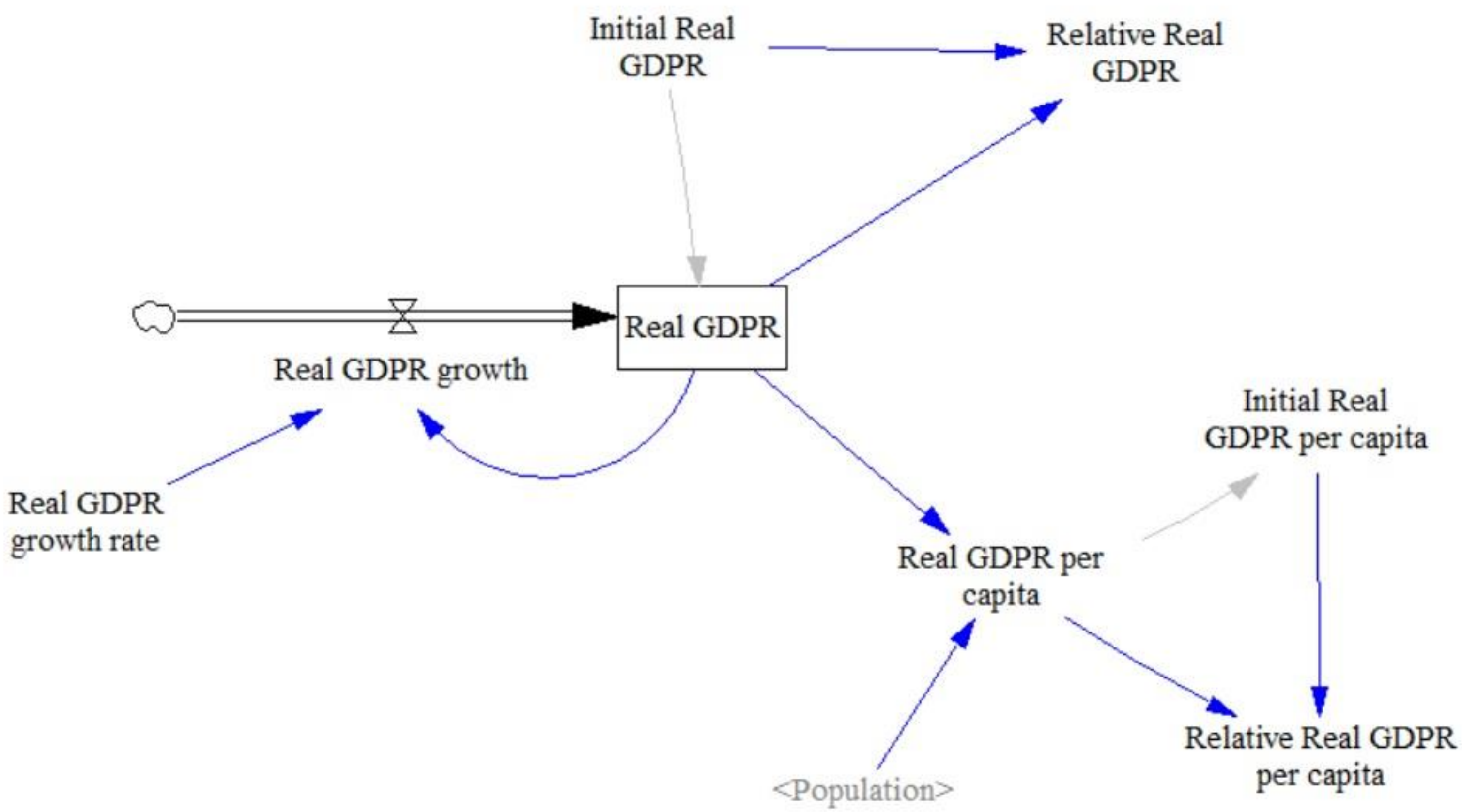

Figure 81: Regional gross domestic product sub-model

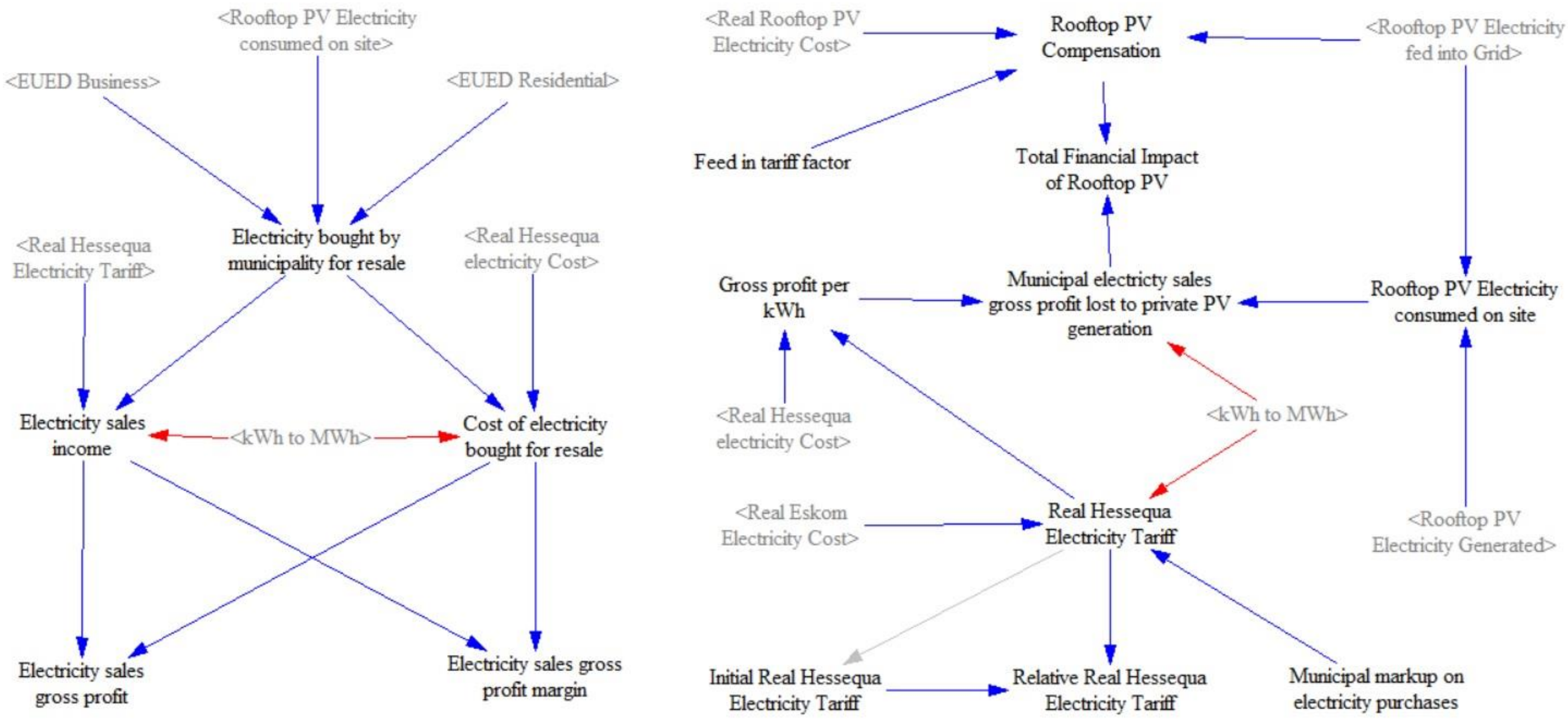

Figure 82: Municipal impacts sub-model

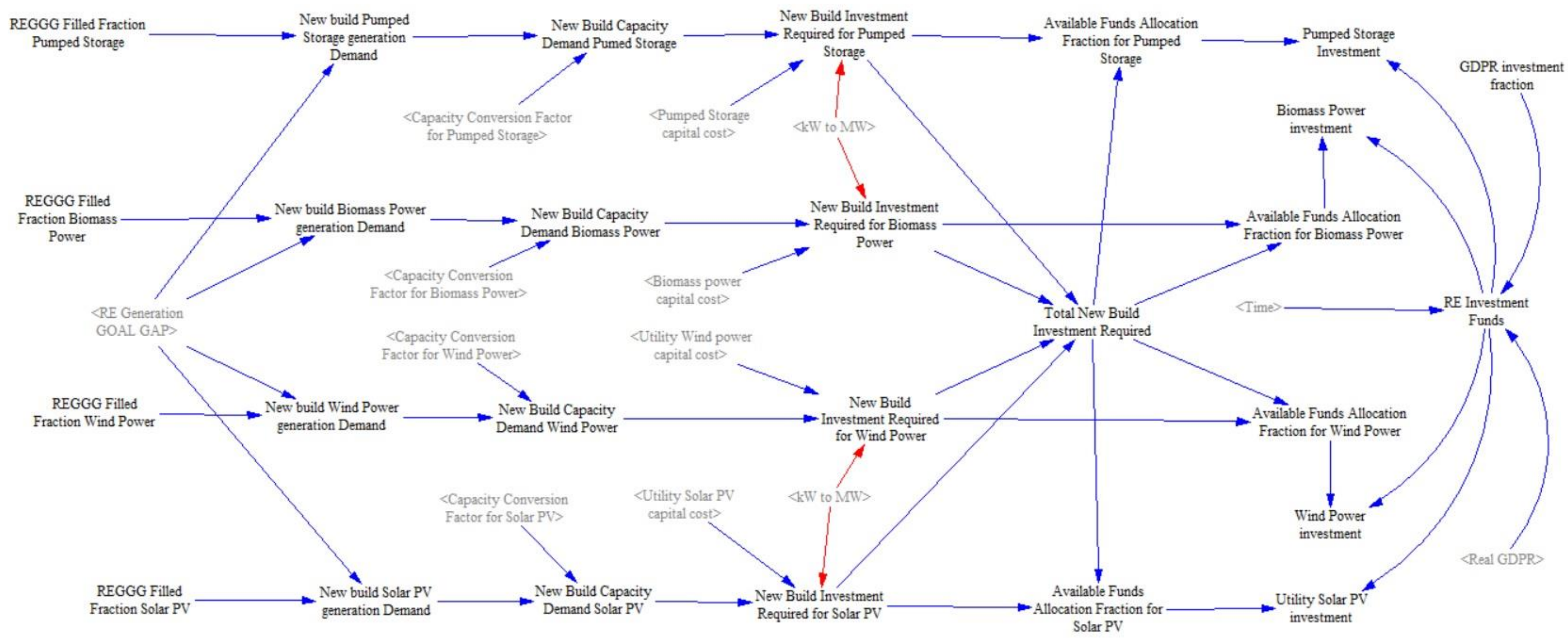

Figure 83: Investment sub-model 1

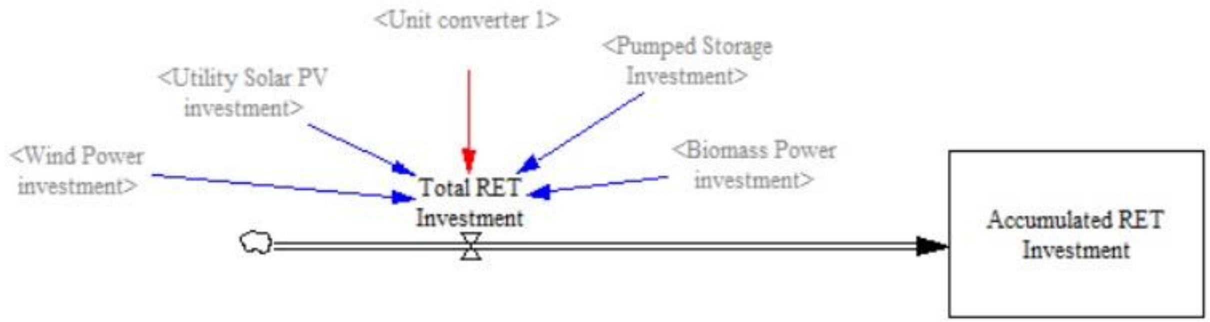

Figure 84: Investment sub-model 2

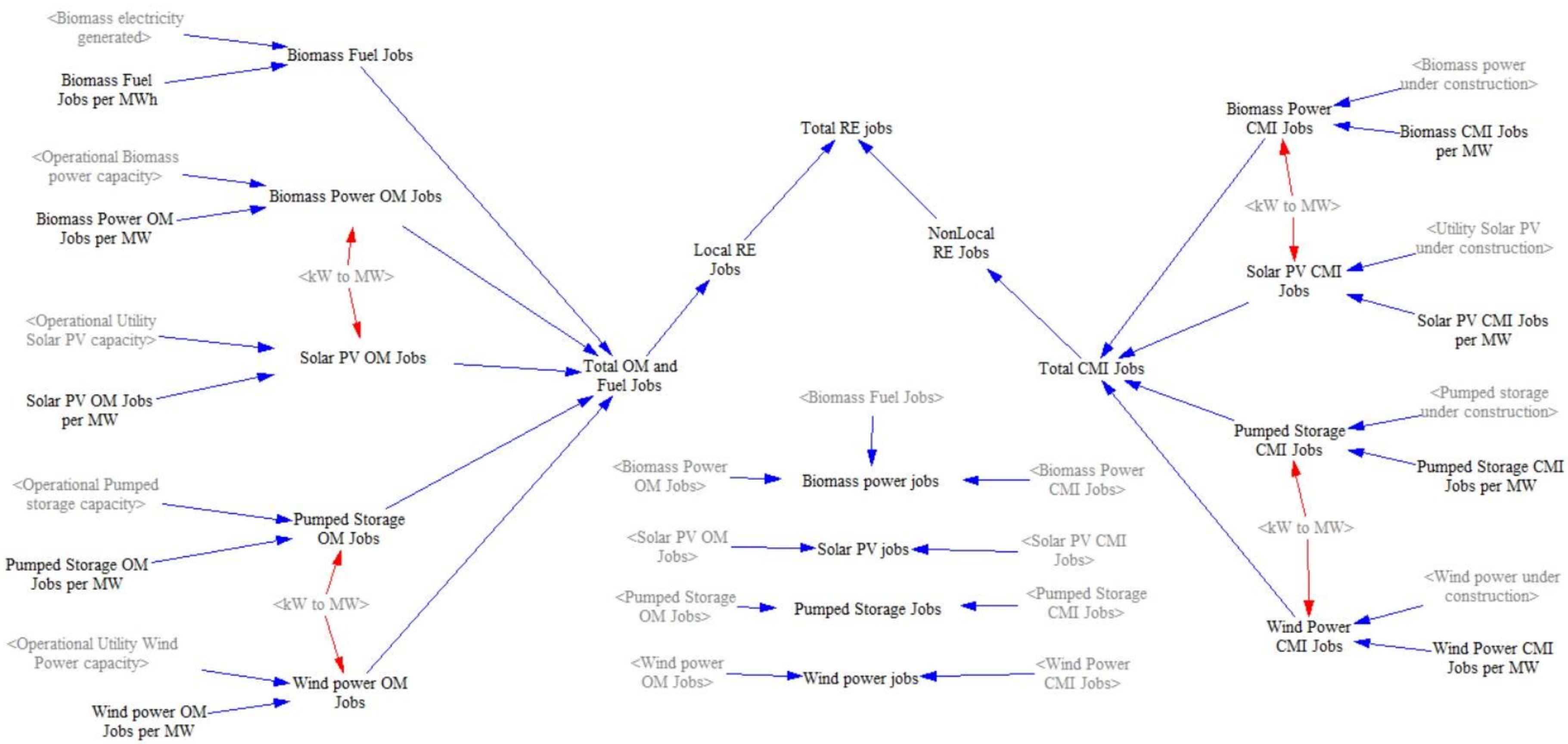

Figure 85: Employment sub-model

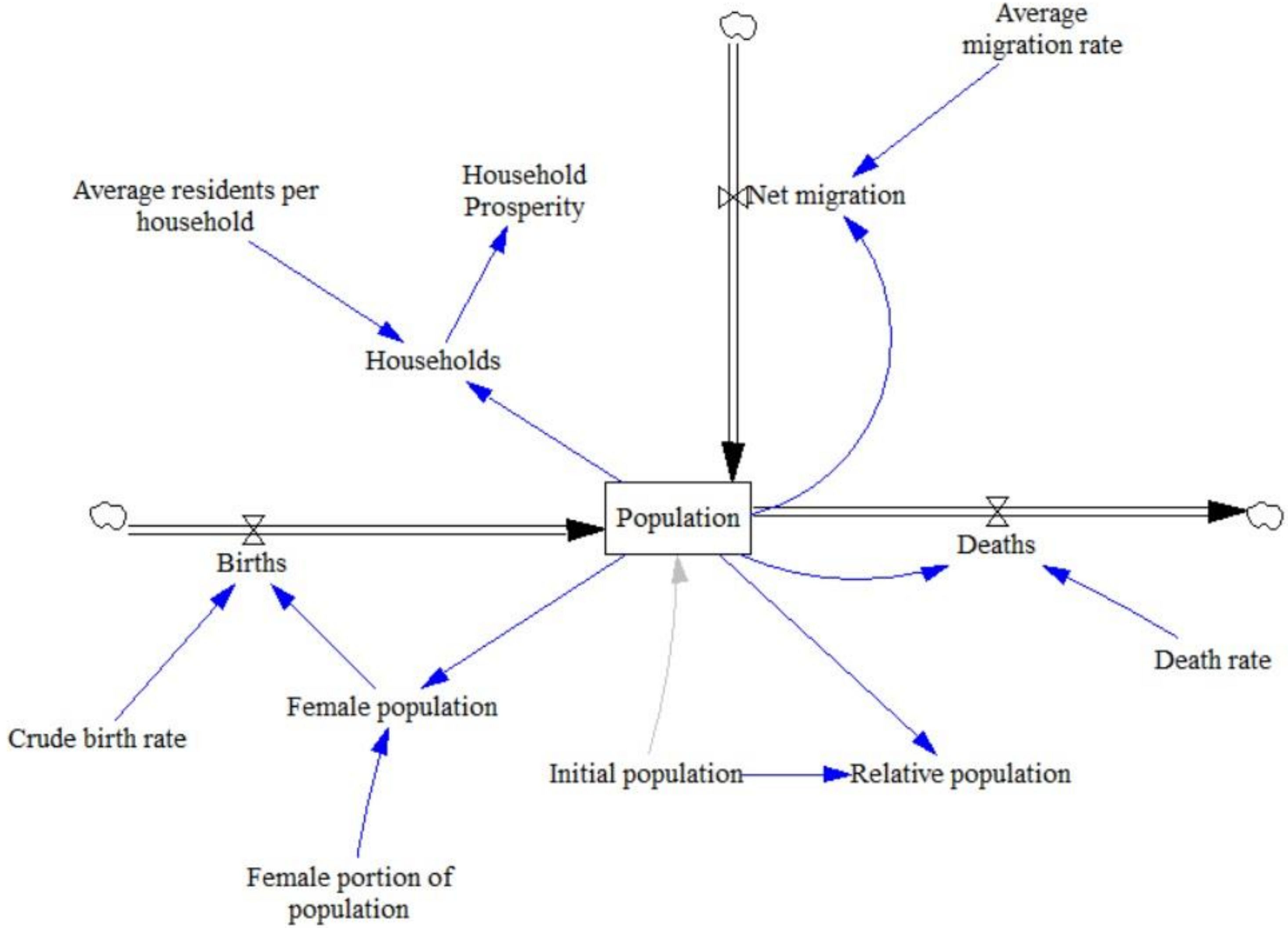

Figure 86: Population sub-model

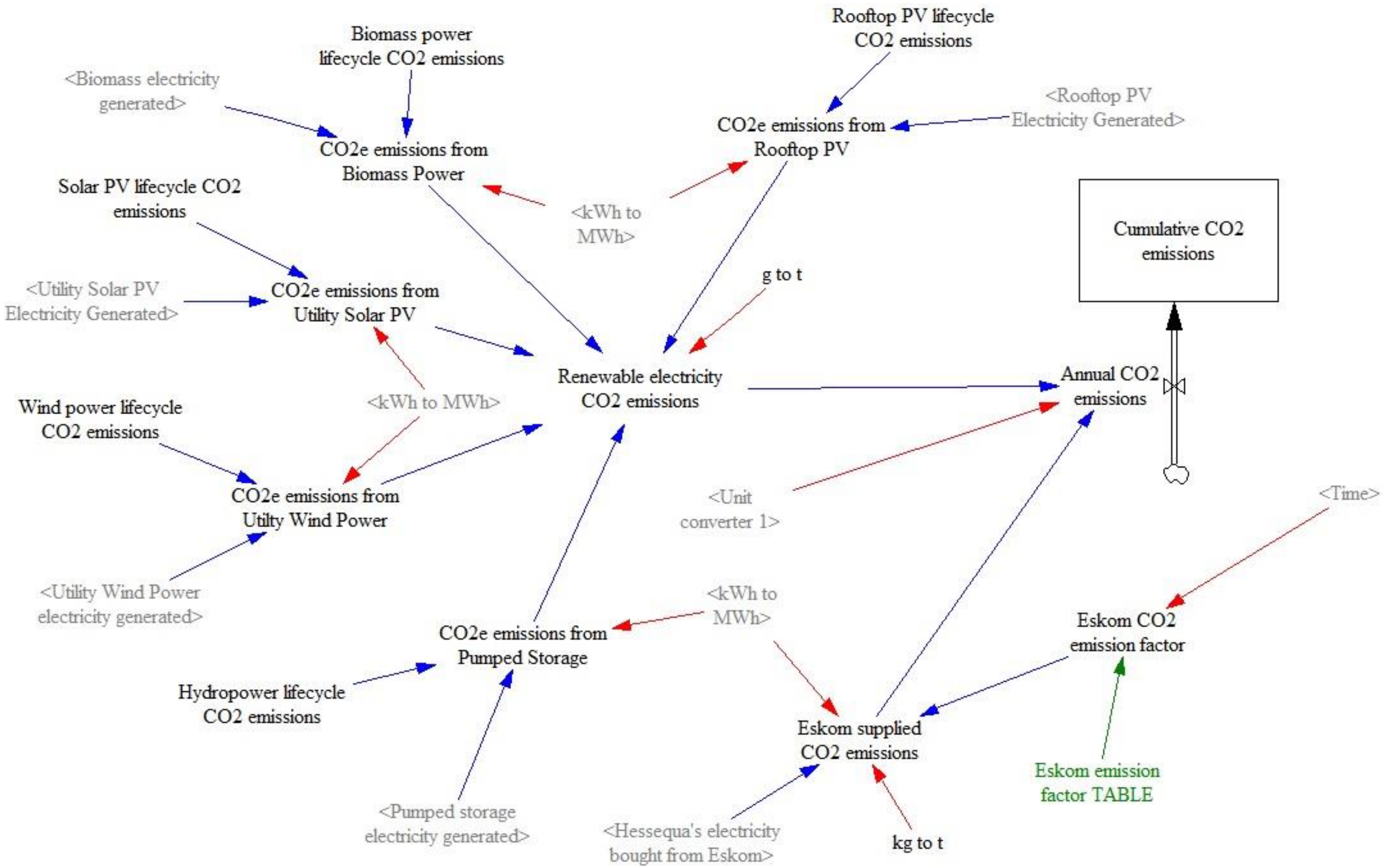

Figure 87: Emissions sub-model

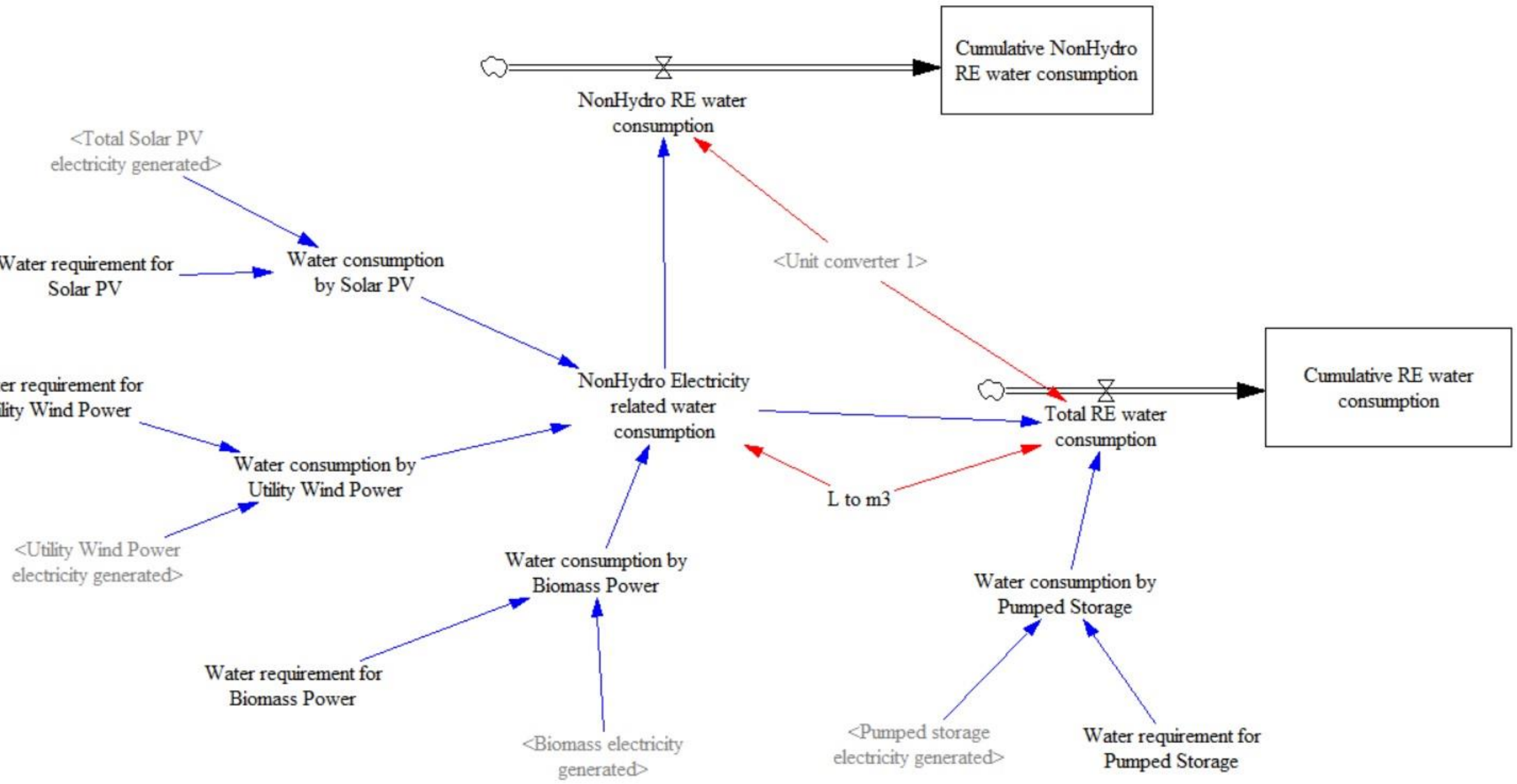

Figure 88: Water consumption sub-model